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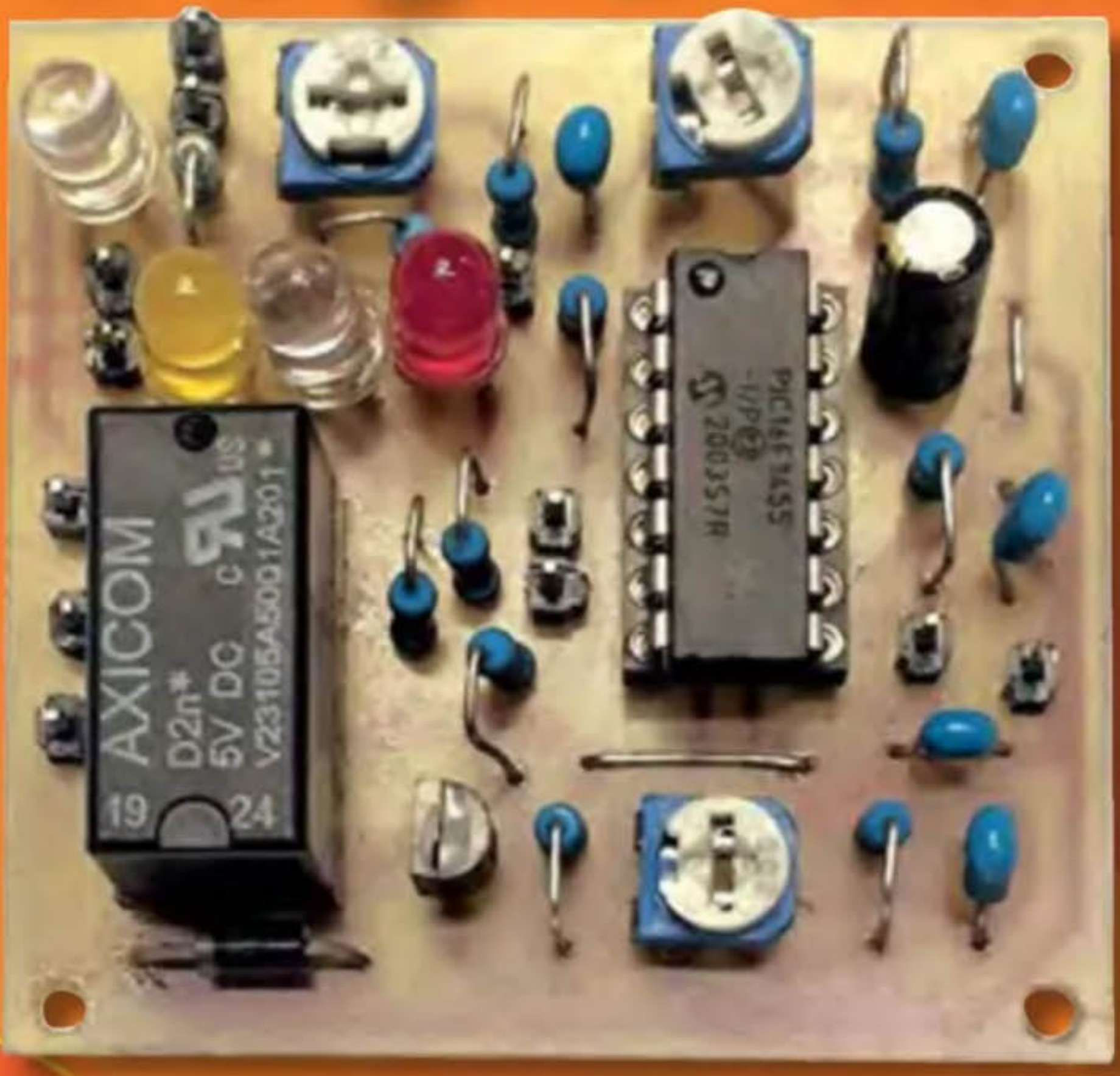

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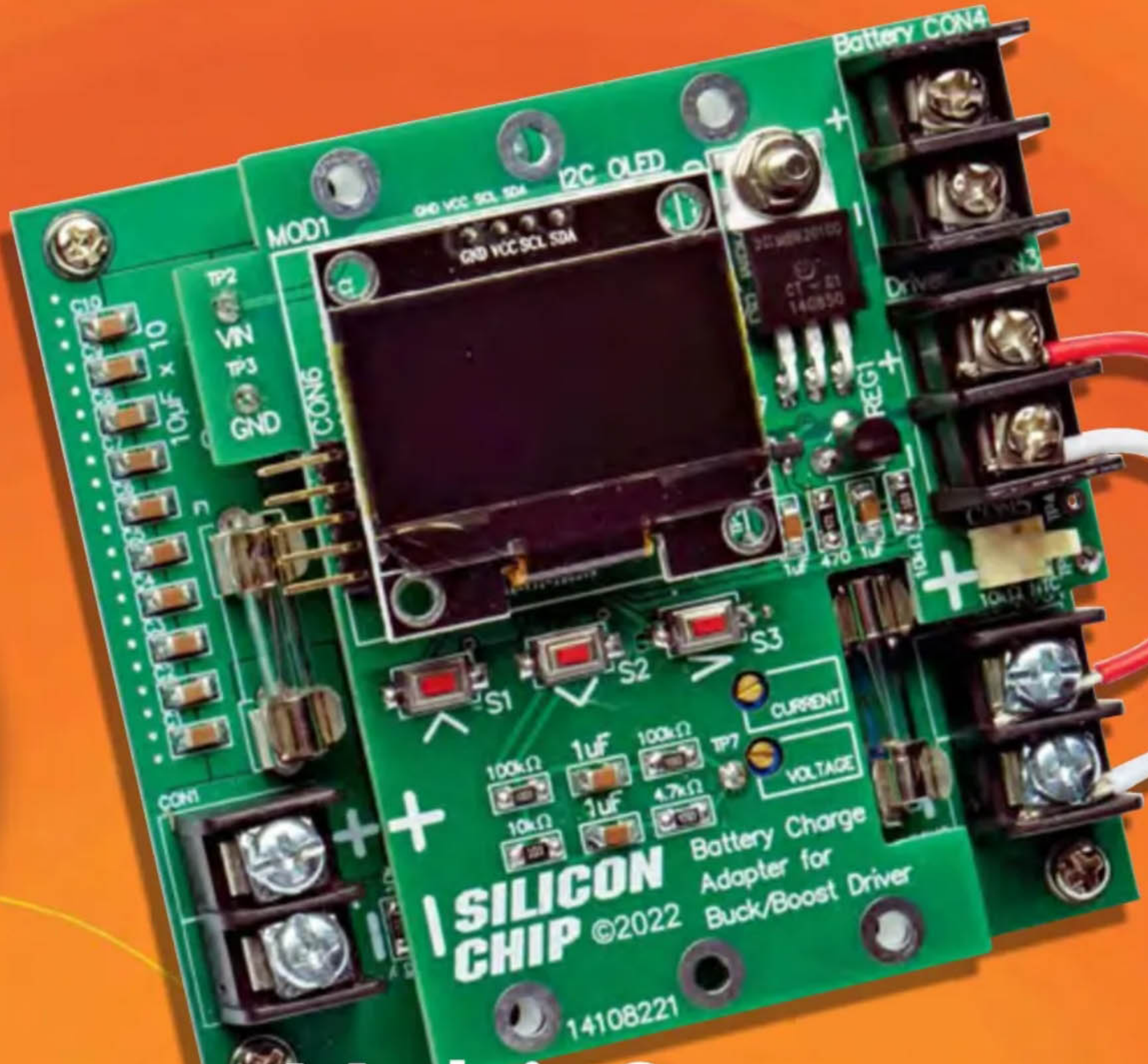

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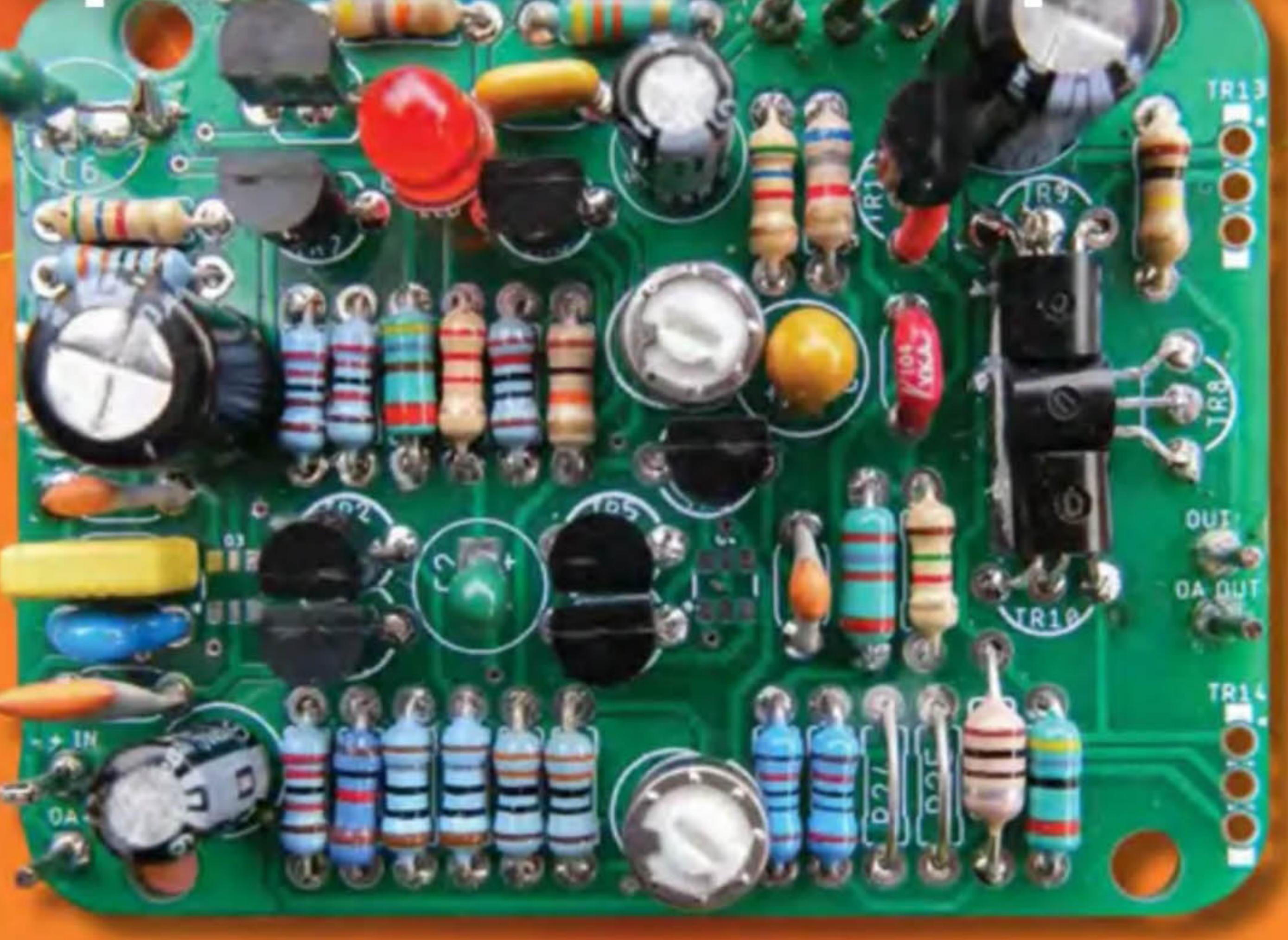

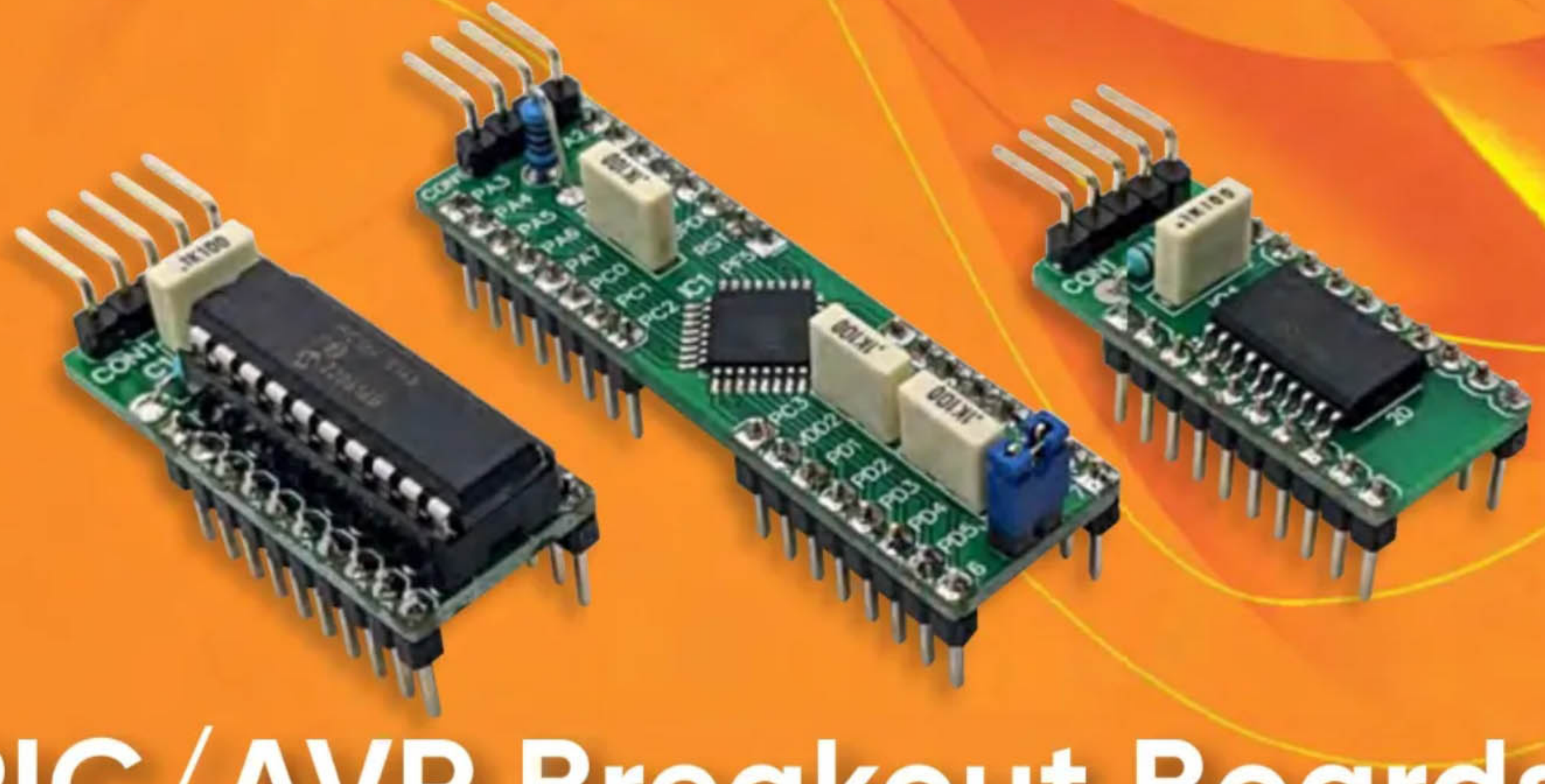

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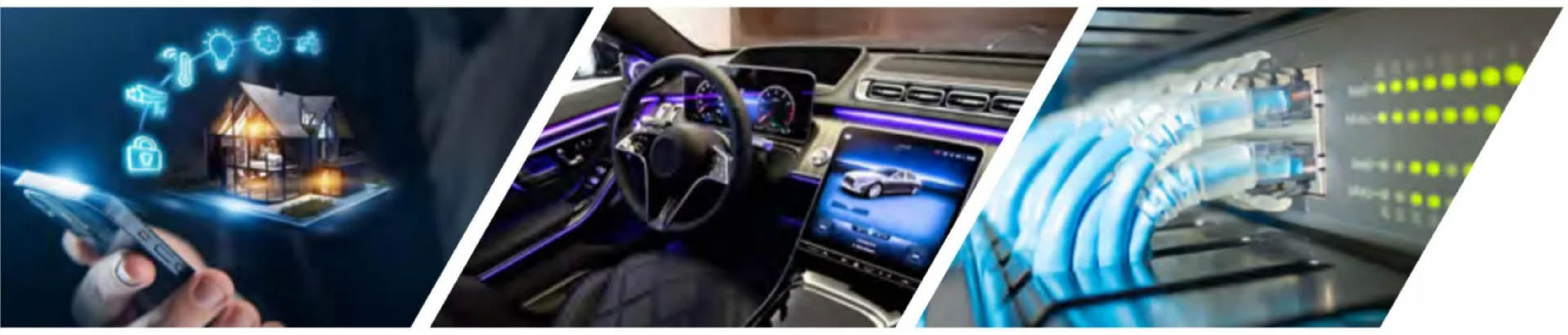

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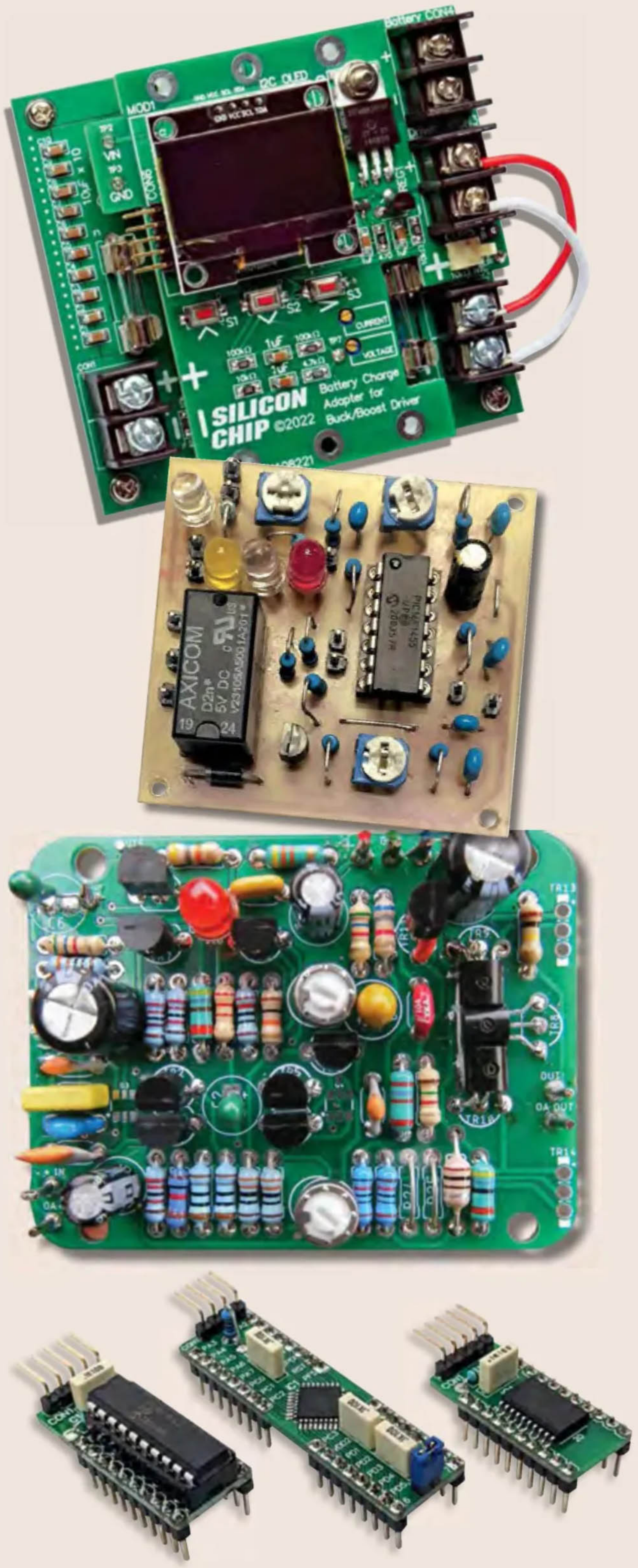

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The November 2023 issue of *Practical Electronics* will be published on Thursday, 5 October 2023 – see page 72.

WIRELESS FOR THE WARRIOR

by LOUIS MEULSTEE

THE DEFINITIVE TECHNICAL HISTORY OF RADIO COMMUNICATION EQUIPMENT IN THE BRITISH ARMY

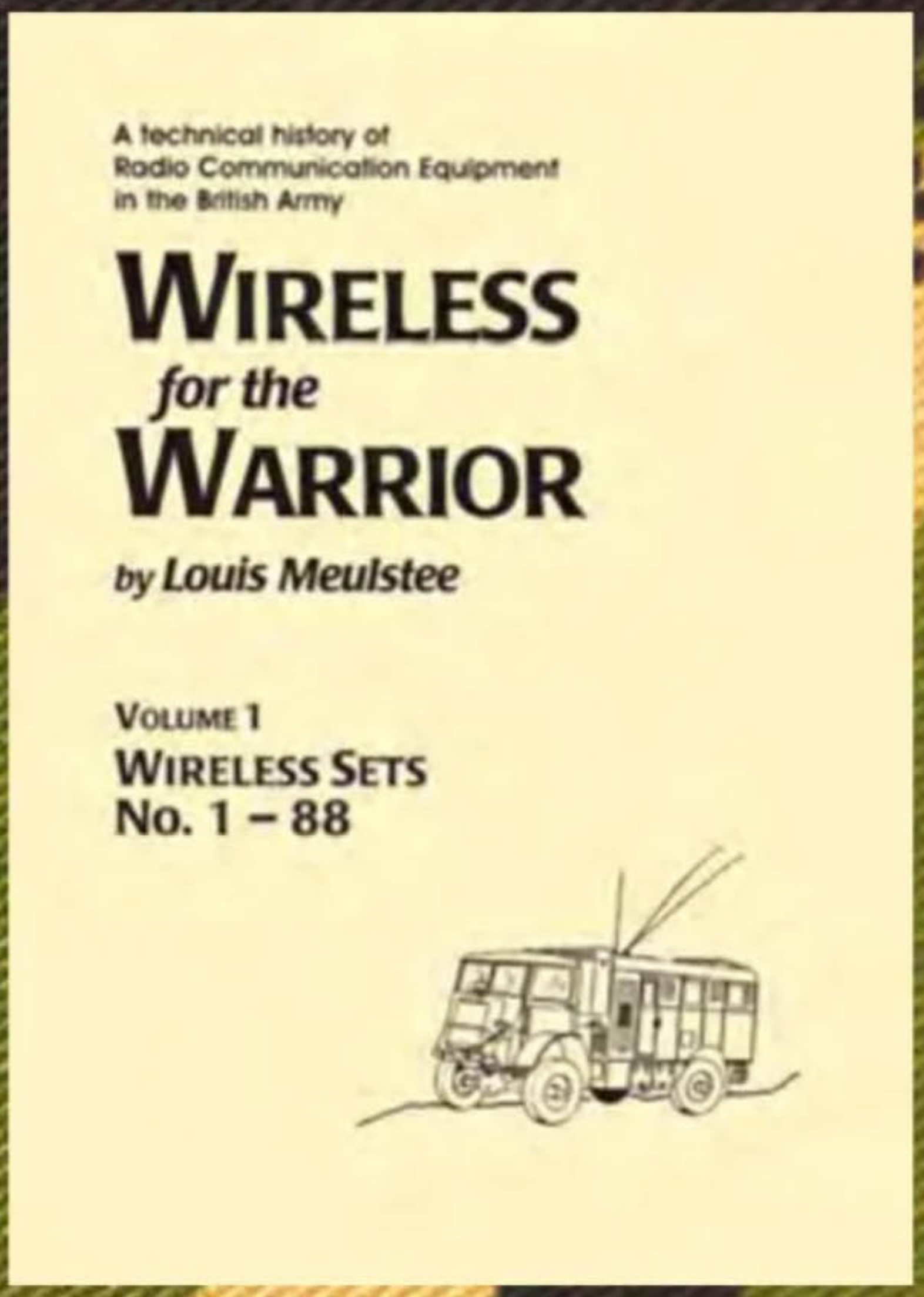
The *Wireless for the Warrior* books are a source of reference for the history and development of radio communication equipment used by the British Army from the very early days of wireless up to the 1960s.

The books are very detailed and include circuit diagrams, technical specifications and alignment data, technical development history, complete station lists and vehicle fitting instructions.

Volume 1 and *Volume 2* cover transmitters and transceivers used between 1932-1948. An era that starts with positive steps taken to formulate and develop a new series of wireless sets that offered great improvements over obsolete World War I pattern equipment. The other end of this timeframe saw the introduction of VHF FM and hermetically sealed equipment.

Volume 3 covers army receivers from 1932 to the late 1960s. The book not only describes receivers specifically designed for the British Army, but also the Royal Navy and RAF. Also covered: special receivers, direction finding receivers, Canadian and Australian Army receivers, commercial receivers adopted by the Army, and Army Welfare broadcast receivers.

Volume 4 covers clandestine, agent or 'spy' radio equipment, sets which were used by special forces, partisans, resistance, 'stay behind' organisations, Australian Coast Watchers and the diplomatic service. Plus, selected associated power sources, RDF and intercept receivers, bugs and radar beacons.



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in the British Army

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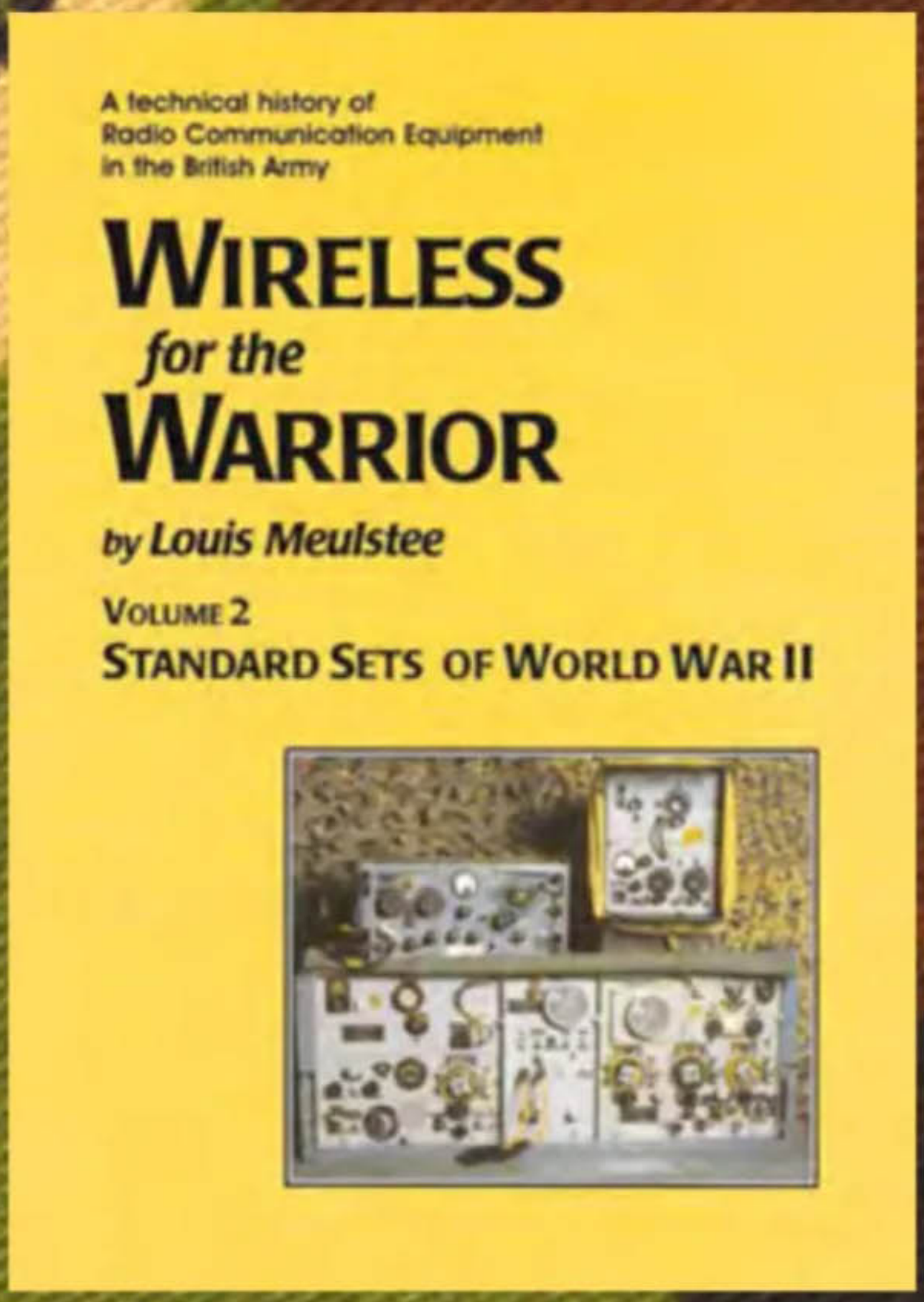

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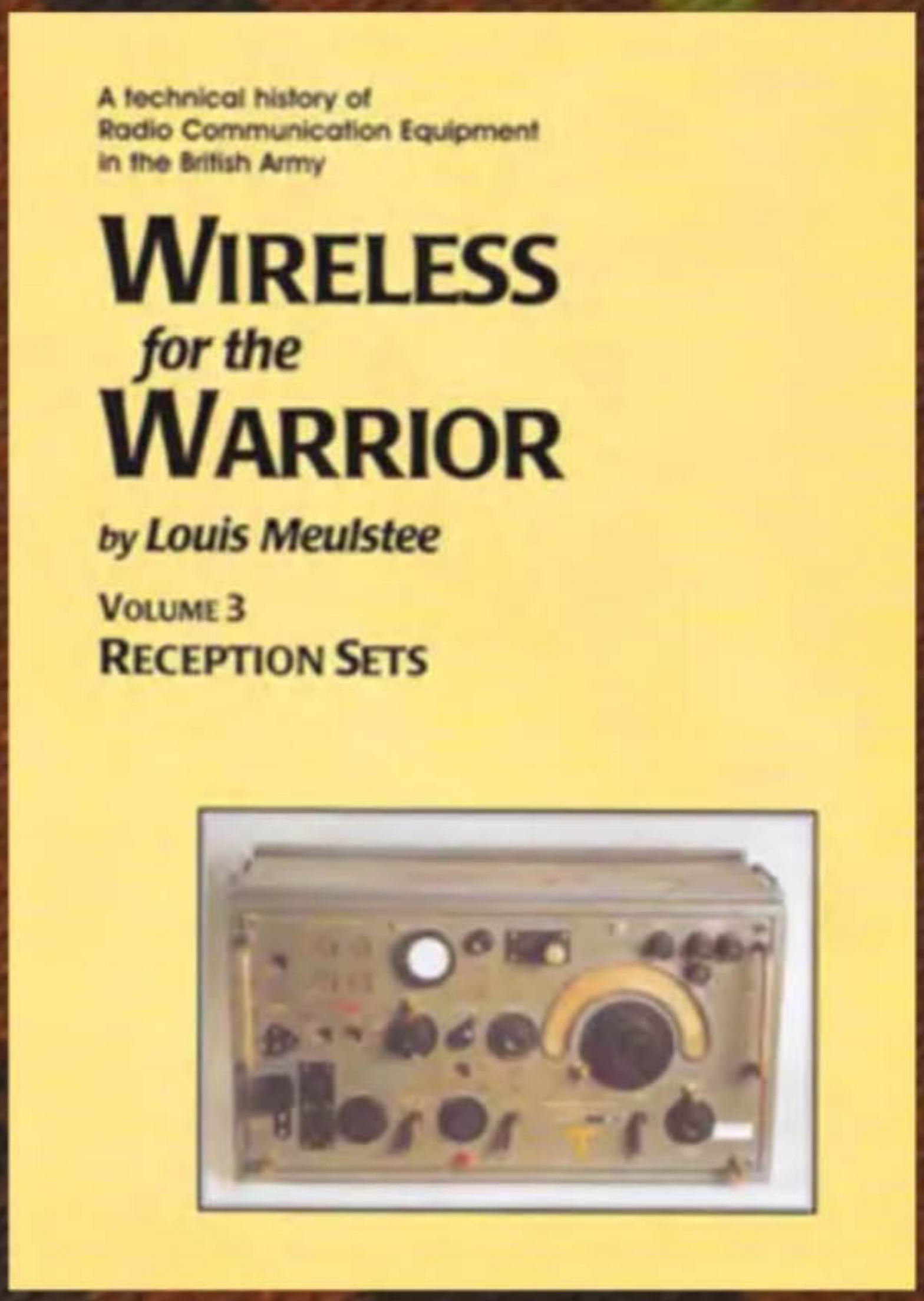

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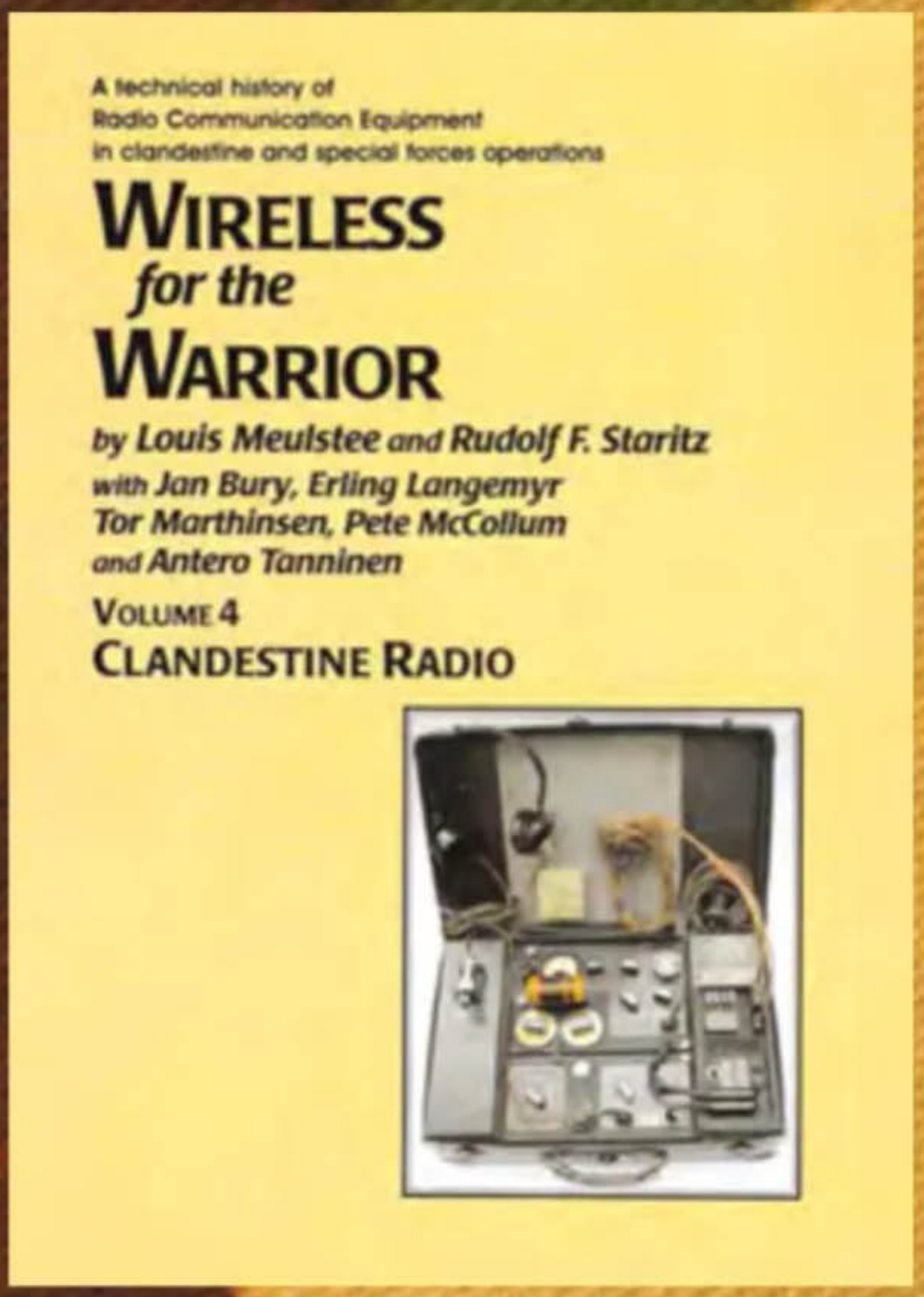

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in clandestine and special forces operations

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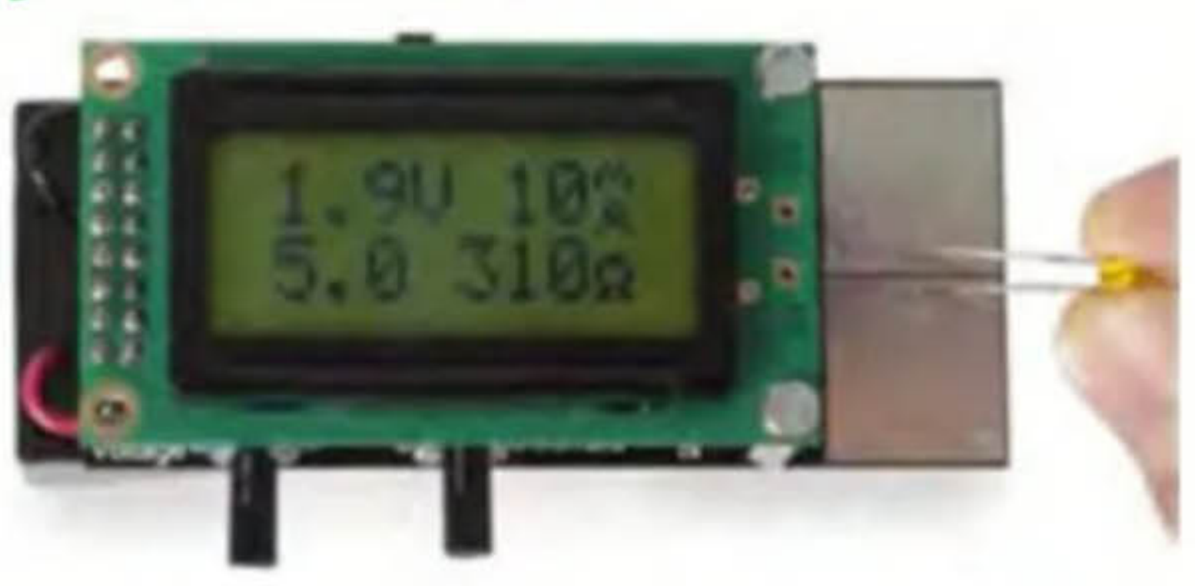


Hold any type of LED to the contact pads to see it's polarity, forward voltage & the recommended series resistor value. Adjustable target current & forward voltage. Great design aid.
*Order Code: WSMI198 - **£16.66***

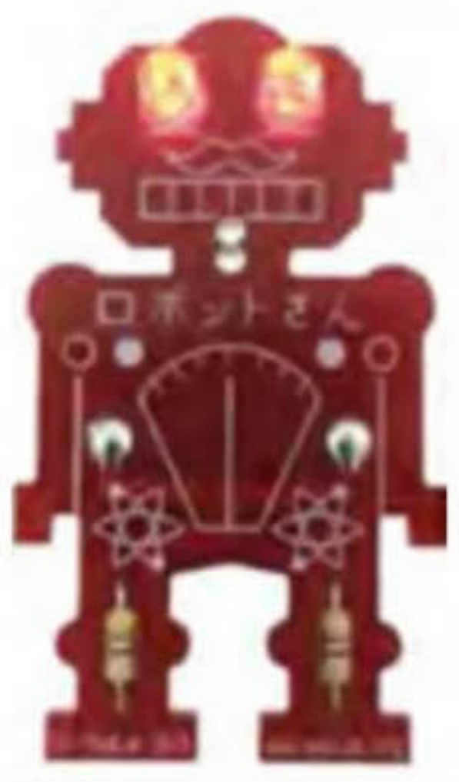
12-in-1 Solar Hydraulic Construction Kit

Solar & hydraulic powered robot can be transformed into twelve different animals and mechanical robots (monkey, T-Rex, scorpion, excavator, etc). Moves easily. Provides great interaction with kids. Teaches the benefit of alternative energy. Aged 14+.
*Order Code: KSR17 - **£29.95.***

Stereo Ultrasonic Bat Detector Kit

Educational & fun kit converts high frequency sounds (20 - 90kHz) normally imperceptible to humans like bat signals into audible noise. Can also help detect failures in machines, engines, etc. Stereo feature adds the possibility to pinpoint the source. Frequency range 20-90kHz. 3.5mm jack output. 129x60x40mm. Requires 3x AA batteries and stereo headphones (not included).
*Order Code: WSAK8118 - **£20.39***

NEW! Mr Robot Kit



A fun, wearable electronic gadget that you can pin to your clothes. Easy to solder beginners kit. Two flashing bicolour LEDs resemble the eyes. 65 x 40 x 15 mm. CR2032 battery powered (not included).
Order Code: WSL108 - 6.68

LED Electronic Dice Kit

Still popular! A must-build soldering kit for all beginners. Dice slowly rolls to stop on a random number when the push button is released. 9V battery (not included). Ideal for educational courses. Wide selection of component types.
*Order Code: MK109 - **£7.08***

3 Channel RGB LED Light Organ Kit

Sens
Low R
Mid G
High B
velleman R-G-B LED light organ

3 outputs react to different sound frequencies. On-board microphone picks up surrounding sound or music and drives the low, mid & high frequency outputs. Connect 12-24Vdc RGB or separate colour LED strips or LEDs (not included). Master & separate channel sensitivity adjustment. 1.25 A max. per channel. Panel mountable facia 127 x 44mm. Terminal block or jack power supply connection. Control knobs included.
*Order Code: WSL209 - **£14.10***

Signal Generator Kit

Sine wave, triangle, square wave and integrator (selectable through jumper) with 0 - 100Vrms adjustable output level. 1kHz (approx.) fixed signal frequency. 9V battery (not included).
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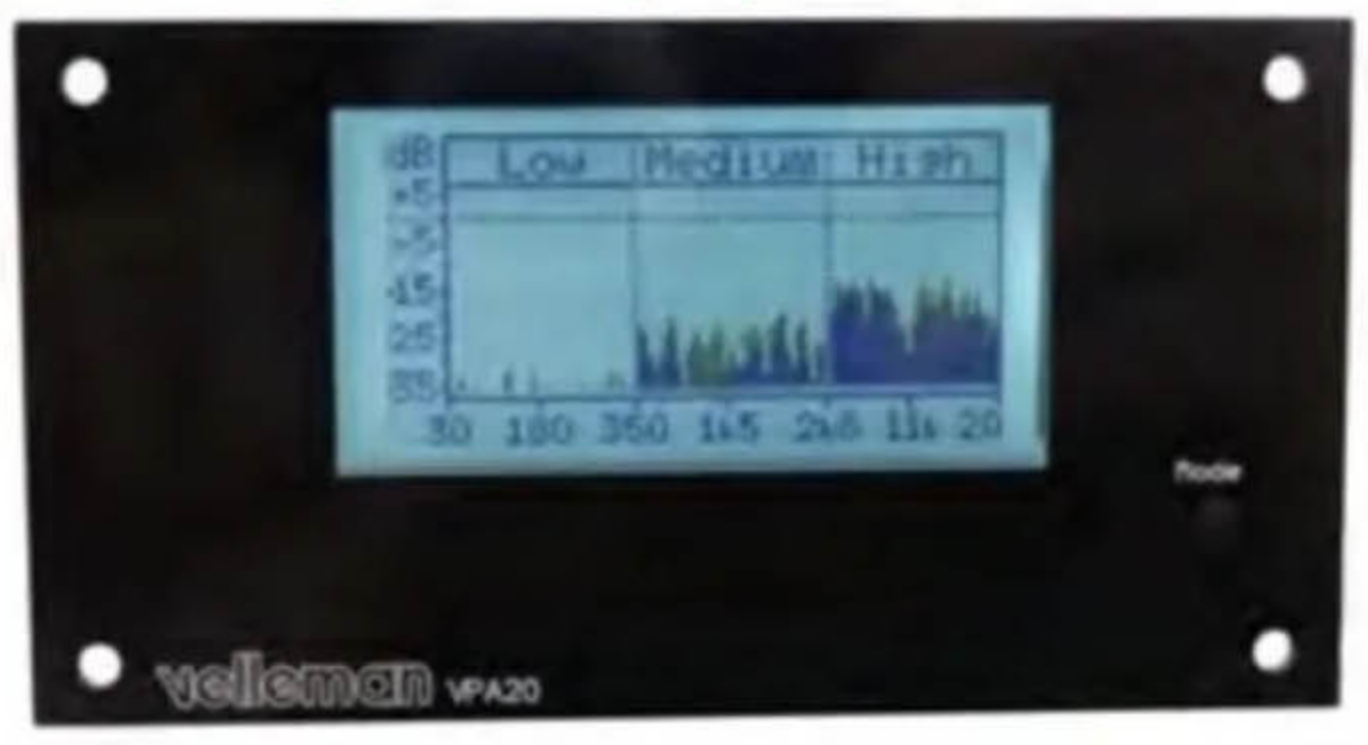
Digitally Controlled FM Radio Kit

Build your own modern, high quality FM receiver project with excellent sensitivity powered by a simple 9V PP3 battery (not included. Auto-seeking button. 4 station presets. Volume control. Excellent learning project for schools and colleges.
*Order Code: WSAH194 - **£20.39***

Audio Analyser Display Kit



Small, compact LCD display, ideal for panel mounting. Give your homemade audio gear a high-tech look. Upgrade existing equipment. Provides Peak Power, RMS Power, Mean dB, Peak dB, Linear Audio Spectrum And 1/3 Octave Audio Spectrum. Auto / Manual range selection. Peak-hold function. Speaker impedance selection.
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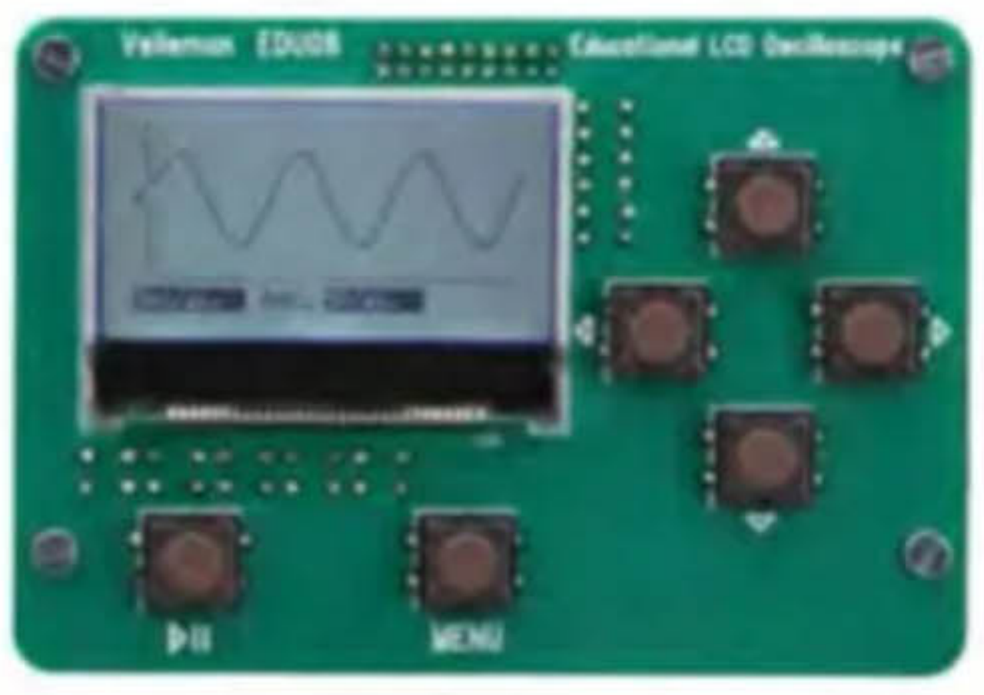
LCD Oscilloscope Educational Kit



Build your own LCD oscilloscope with this exciting new kit. Learn how to read signals. See the electronic signals you learn about displayed on your own LCD oscilloscope. Despite the low cost, this oscilloscope kit has a lot of features found on expensive units like signal markers, frequency, dB, true RMS readouts and more. A powerful auto-setup function will get you going in a flash!
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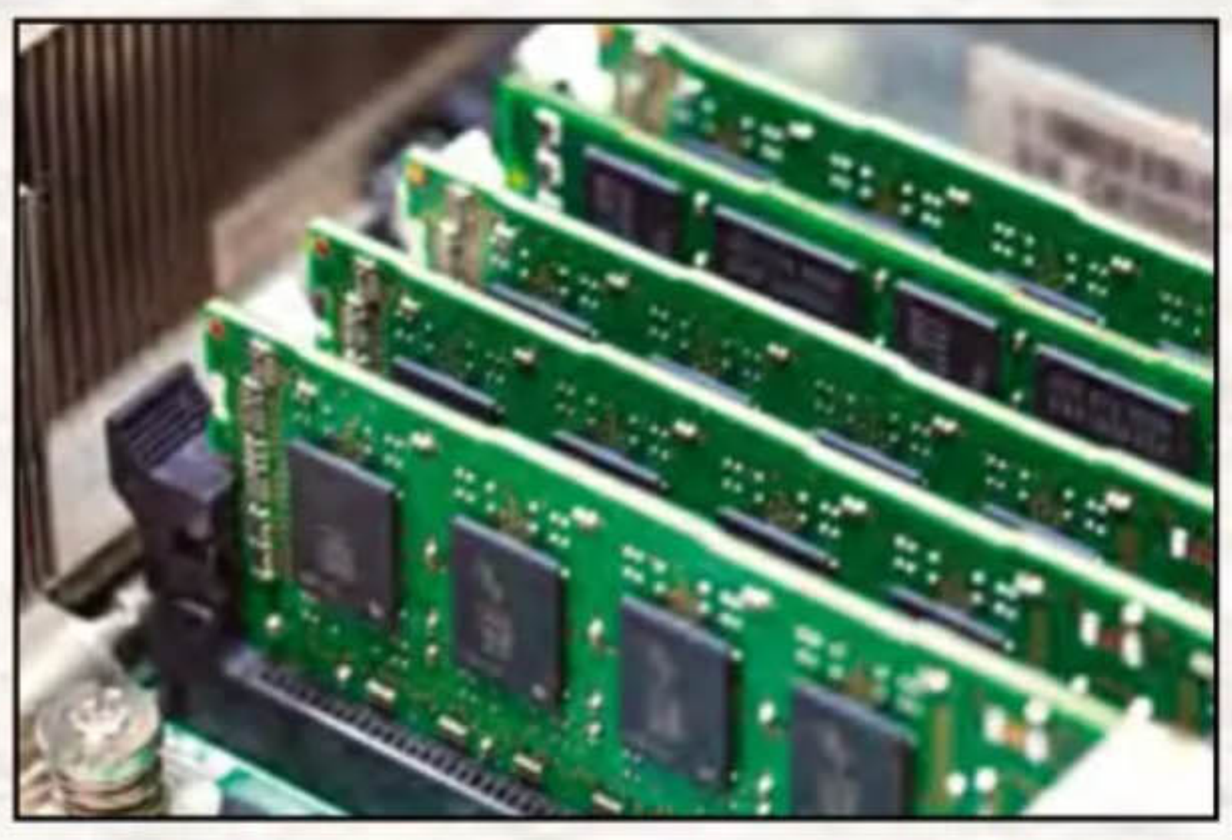
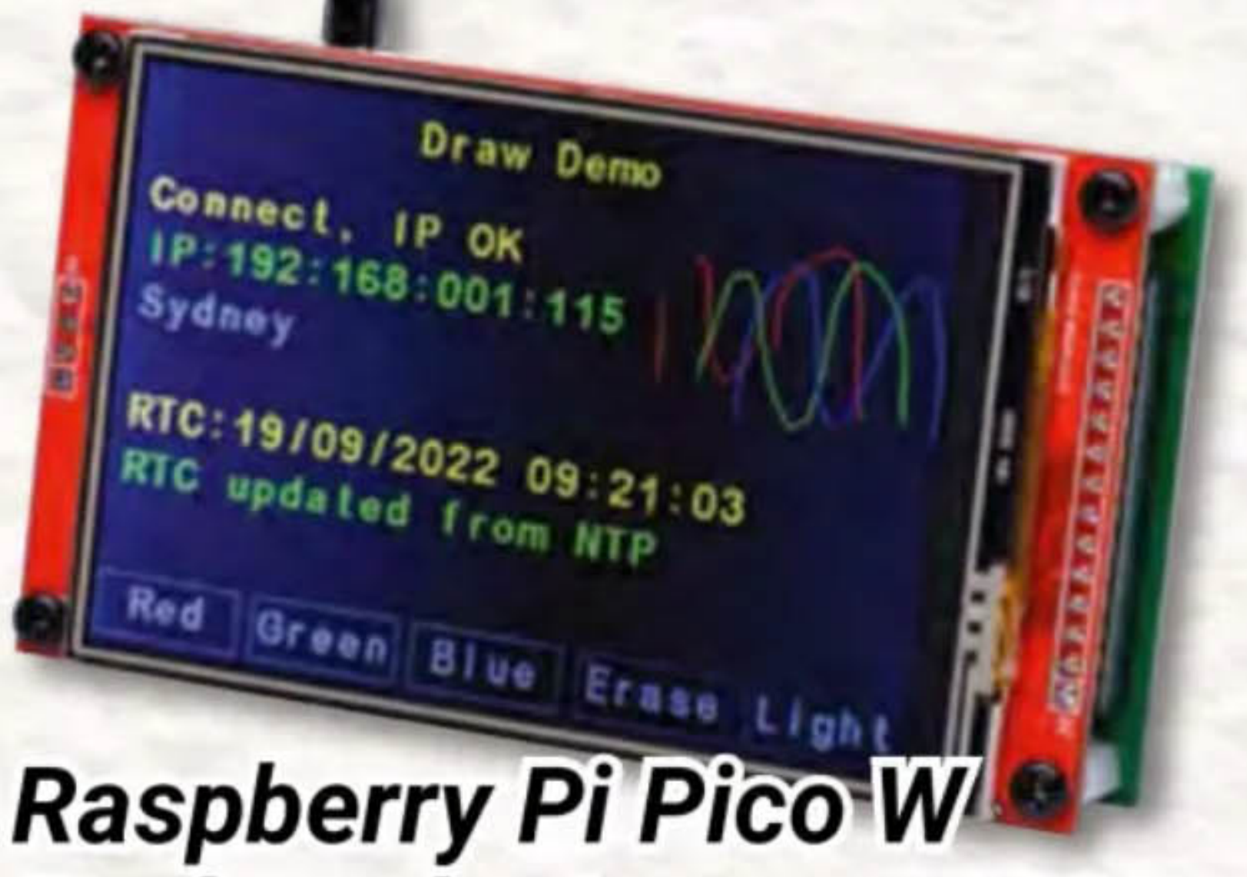


The History of Computer Memory; Jan-Feb 2023



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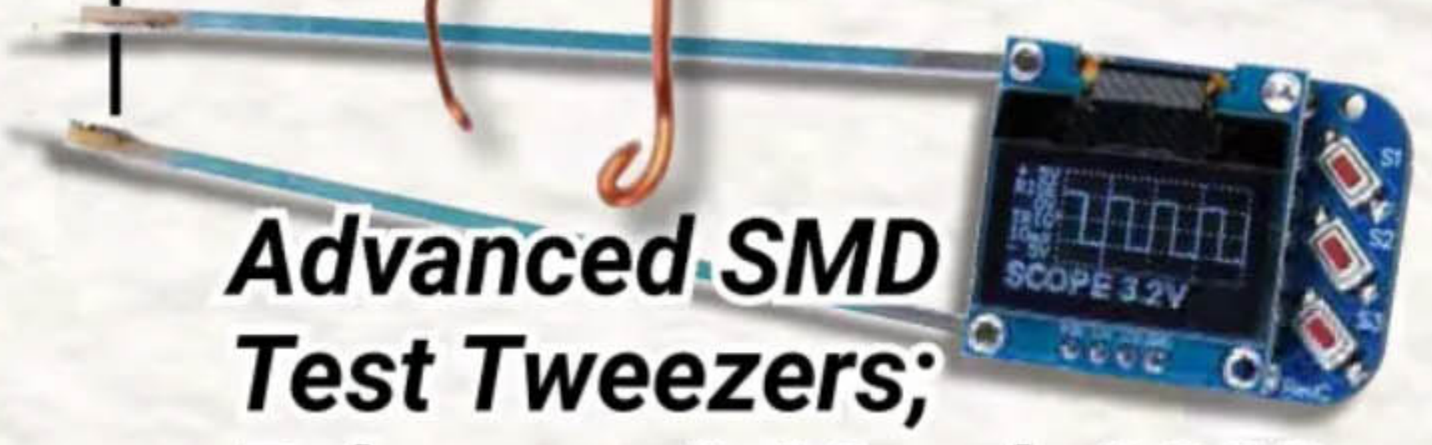

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Time for some new PICs

Your mileage may vary, but for many of us, the defining new semiconductor technology of the last dozen years has been the irresistible rise of inexpensive, easy-to-program and easy-to-use microcontrollers. Leading the pack in this field is of course Microchip, with their huge range of PICs. From the simplest of 8-pin devices that cost well under a pound to sophisticated 32-bit DSP devices there seems to be a PIC for practically every application, price point and level of designer experience. Indeed, some have pointed out that one of the hardest things to do with the PIC range is ploughing through the enormous number of devices and package configurations to decide which one to use!

One approach – the one you will consistently find in our projects – is to spend some time choosing a handful of devices and then sticking to that list. This is a good strategy, but sooner or later a refresh becomes inevitable. Devices that were inexpensive and easy to find become scarce and pricey, or a replacement arrives that is cheaper, quicker, more sophisticated and uses less power. This is normal in the semiconductor industry, but over the last few years a real black swan event has forced us to undertake a thorough reappraisal of our PIC choices. The pandemic caused enormous problems with electronics supply chains – you can still regularly find ordinary devices listed with blue-chip international distributors with >52-week lead times. This is particularly true of older devices, which semiconductor companies inevitably view as less important to manufacture compared to their shiny new state-of the-art designs.

So, with all of the above in mind, this month we are looking at some new devices that we will be incorporating in future projects, and which we think you will enjoy using. Plus, we have produced a trio of nice little breakout boards that make connection to a PICkit programmer that much easier.

AVR too

And for those of you who like to use AVR microcontrollers, used extensively in Arduino boards, we've taken a look at new devices from that stable too.

So, whether you are a seasoned and experienced user of PICs, or a newbie looking to dip a toe or two in the microcontroller ocean, we think you will enjoy our article and project on these indispensable devices.

Matt Pulzer
Publisher

Holy Spheres, Batman!

Techno Talk

Max the Magnificent

My mind is boggled with respect to emerging tools and technologies that are allowing us to create awesome artifacts and to explore the universe in ways that would have appeared impossible a few scant years ago.

I'm sure that, like me, you've been entranced by what you've seen and heard about the Sphere at The Venetian Resort in Las Vegas. Costing \$2.3bn (which means I won't be buying one of my own in the foreseeable future), this bodacious beauty is the largest spherical building in the world at 81,300m^2 of exterior area.

Inside the Sphere we find seating for 18,600 people. The multi-layered audio system boasts 160,000+ speakers and uses 3D audio beamforming technology that promises to present a targeted, crystal-clear, and uniform sound experience to every seat in the house. Some say this will be an audio experience to die for, which might be both figuratively and literally true if hackers ever manage to take control of the system.

In addition to the awesome audio, 10,000 of the seats incorporate an infrasound haptic system that will allow their incumbents to experience 4D features, such as changing temperatures, breezes, scents, and so forth. The interior flaunts a 16K-resolution (19,000 × 13,500 pixels!) wraparound LED screen, measuring 15,000m^2, thereby making it the largest and highest-resolution LED screen in the world. The venue is scheduled to open on 29 September, 2023, with U2 as its first performer (I wish I could see that).

I have no doubt that the inside of the Sphere will be stunning (I'm already straining at the seams for superlatives), but it's the outside of the beast that makes me want to squeal in excitement. The exterior surface will features 54,000m^2 of programmable lighting in the form of 1.2 million hocky-puck-sized LED arrays, each containing 48 individual tricolor diodes, all of which can be used to present the most awesome displays. Just perform a Google search for 'YouTube Sphere Las Vegas' and prepare to have your mind well and truly boggled: **https://youtu.be/wKCY1Ph7T0k**

How much power are we talking about here? Well, these are super-bright LEDs, so let's assume 10W per puck, which gives us (1.2 × 10^6 pucks) × 10W = 12MWh over the course of an hour. According to the Office of Gas and Electricity Markets (Ofgem), a typical household in Britain uses approximately 3MWh of electricity annually. This equates to an average of (3 × 10^6) / (365 days/year) / (24 hours/day), which equals 342Wh per hour, give or take. Thus, whenever the outside of the Sphere is operating at its full potential, it's consuming the same amount of power as around 35,000 houses in the UK! (I'm glad I don't have to pay that electricity bill.)

I can't take the strain. All this talk of LEDs and spheres has made me want to build my own, like the one created by Jiri Praus: **https://bit.ly/45oTWGA**

What time is it?

For reasons we don't need to discuss here, I've recently been learning a lot more about packet-based networks than I ever really wanted to know. To work their magic, all the elements forming the network must be synchronised in time.

Establishing and measuring the level of simultaneity – the temporal ordering of events – requires those events to be 'timestamped.' In turn, it's necessary for all the devices forming the network to be synchronised to a common 'grandmaster clock.'

Of course, we have access to tremendously accurate clocks these days. For example, according to the boffins at the National Institute of Standards and Technology (NIST), there's a strontium atomic clock so accurate it would not have gained or lost a second had it started running at the dawn of the universe. The problem is that clocks of this ilk are the opposite of cheap, and you certainly can't afford to stick one in every switch and router forming a network.

The solution for packet-based networks is to use something called the Precision Time Protocol (PTP), a.k.a. IEEE 1588, which can achieve accuracy in the sub-microsecond range. In this case, whichever subsystem is connected to the grandmaster clock – let's call it the upstream unit – sends a packet to a downstream unit stamped with the time of departure derived from the grandmaster clock. The downstream unit stamps the packet with its time of arrival based on that unit's internal clock, which may be out of sync with the upstream unit. The downstream unit then returns the packet to its originator, adding the new time of departure. In turn, the upstream unit appends the packet's new time of arrival.

Using these four timestamp values, the upstream unit can determine the error in the downstream unit's clock and instruct it to adjust itself accordingly. Like many things, this seems simple if you say it quickly and then point out of the window and shout, 'SQUIRREL!' In reality, it's horrendously complicated because each outgoing and incoming packet may take a different path (and hence have a different delay) through the network. Also, the downstream unit's clock may drift over time. This means the two units are obliged to keep on passing packets back and forth, constantly refining their level of synchronisation.

The problem is only exacerbated by the fact that the primary unit may be connected to multiple downstream units. In turn, each of these downstream units will assume the role of a source clock to any of its subordinates, and so it goes down the chain. My head hurts just thinking about all this.

Great balls of fire

There's so much more I wanted to talk about, like the fact that the telescopes and technologies used by astronomers are now so incredibly accurate and precise that they've discovered a star 1,300 light years from us that rotates once every 15 minutes. The truly amazing thing about this 'two-faced' star is that one side is hydrogen while the other side is helium. How can this be? I have no idea.

One last thing I *really* have to tell you is… OK, next month!

Win a Microchip MPLAB ICD 5

Practical Electronics is offering its readers the chance to win a Microchip MPLAB ICD 5 (DV164055) – and even if you don't win, receive a 15%-off voucher, plus free shipping for one of these products.

The MPLAB ICD 5 In-Circuit Debugger/Programmer offers advanced connectivity and power options for developers of designs based on PIC, AVR and SAM devices, and dsPIC Digital Signal Controllers (DSCs). It debugs and programs with the powerful and easy-to-use graphical user interface of MPLAB X Integrated Development Environment (IDE). This next-generation tool offers a variety of capabilities and features that you would normally find in more expensive products to speed up your development and reduce your debug time.

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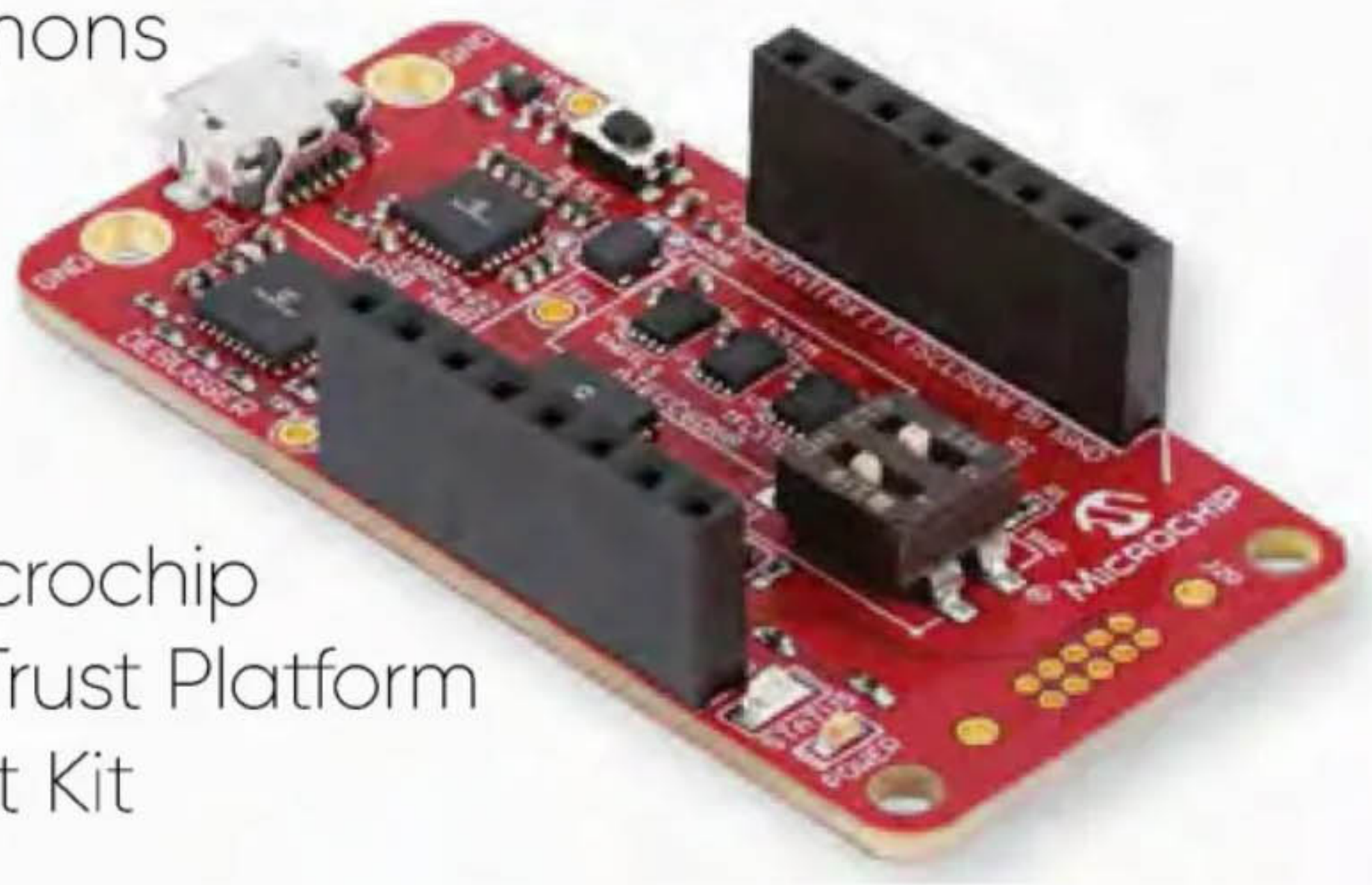
The closing date for this offer is 30 September 2023

June 2022 winner

Charlie Simmons



He won a Microchip CryptoAuth Trust Platform Development Kit

Net Work

Alan Winstanley

This month our Net Work column examines advances in AI-powered image processing and raises the prospect of 'face payments.' There's space news, and advice about dealing with old British paper banknotes.

Artificial intelligence is increasingly being used to help automate complex or high-volume tasks, or to add advanced functionality to something by interpreting and processing streaming data. A taste of things to come was offered by ANPR (Automatic Number Plate Recognition) cameras at least 25 years ago; number-plate-recognition cameras suddenly arrived that extracted data from images of car license plates. Today, ANPR cameras enable London authorities to penalise motorists for driving the wrong type of car in the wrong place at the wrong time, and the police can be alerted when suspect vehicles trigger cameras, or they can check ANPR recorded data afterwards when searching for evidence of a crime.

More than 20 years ago, Logitech's new Face Track feature, licensed from a US tech startup, could magically centre your face automatically in a webcam picture and track it as you moved around. This was a great idea for video calling, although Logitech inexplicably removed it from the drivers of many webcams a few years ago. They now offer 'RightSight' on pricier video conferencing cameras which they say 'uses AI to detect people and frame people to create more immersive meeting experiences.' Digital cameras also started to recognise a smile and capture a perfectly timed snapshot and, for fun, webcams and smartphones learnt how to superimpose cartoon effects on a subject's facial features. Even cheap IP security cameras can record or sound an alarm, not always very accurately, when human-shaped objects enter the scene.

Facebook and Amazon started using AI to tag faces in images (automatically, to begin with, until it was finally disabled by default) and group them into photo galleries, sorted by date, location or 'face' or whatever users wished. Overwhelmed by the sheer volume of its material, Facebook now relies on AI systems to help moderate its contents. Google Street View AI detects car licence plates and faces and blurs them out of every image, a feat that no amount of human operators could ever achieve. More recently, in Britain it was found that AI systems made a better job of diagnosing breast cancer from mammograms than human consultants generally did. Advances in AI are reaching into surgery, providing pre-op data for surgeons or assisting in robotic medical procedures.

Google Street View uses AI to blur licence plates and faces – most of them anyway.

Face recognition technology

Another example of AI that has been trialled for decades is face recognition technology (FRT). However, due to the surrounding privacy issues in Britain, the uptake of FRT has been very restricted. In July, it was reported that FRT picked out the face of a wanted offender in thronging crowds near Buckingham Palace. The villain triggered a live facial recognition (LFR) mugshot on the Scotland Yard database, and he was quickly arrested. According to the Comparitech website, London is in the top 10 most surveilled cities outside of China – see: **https://bit.ly/pe-oct23-cctv** – the others

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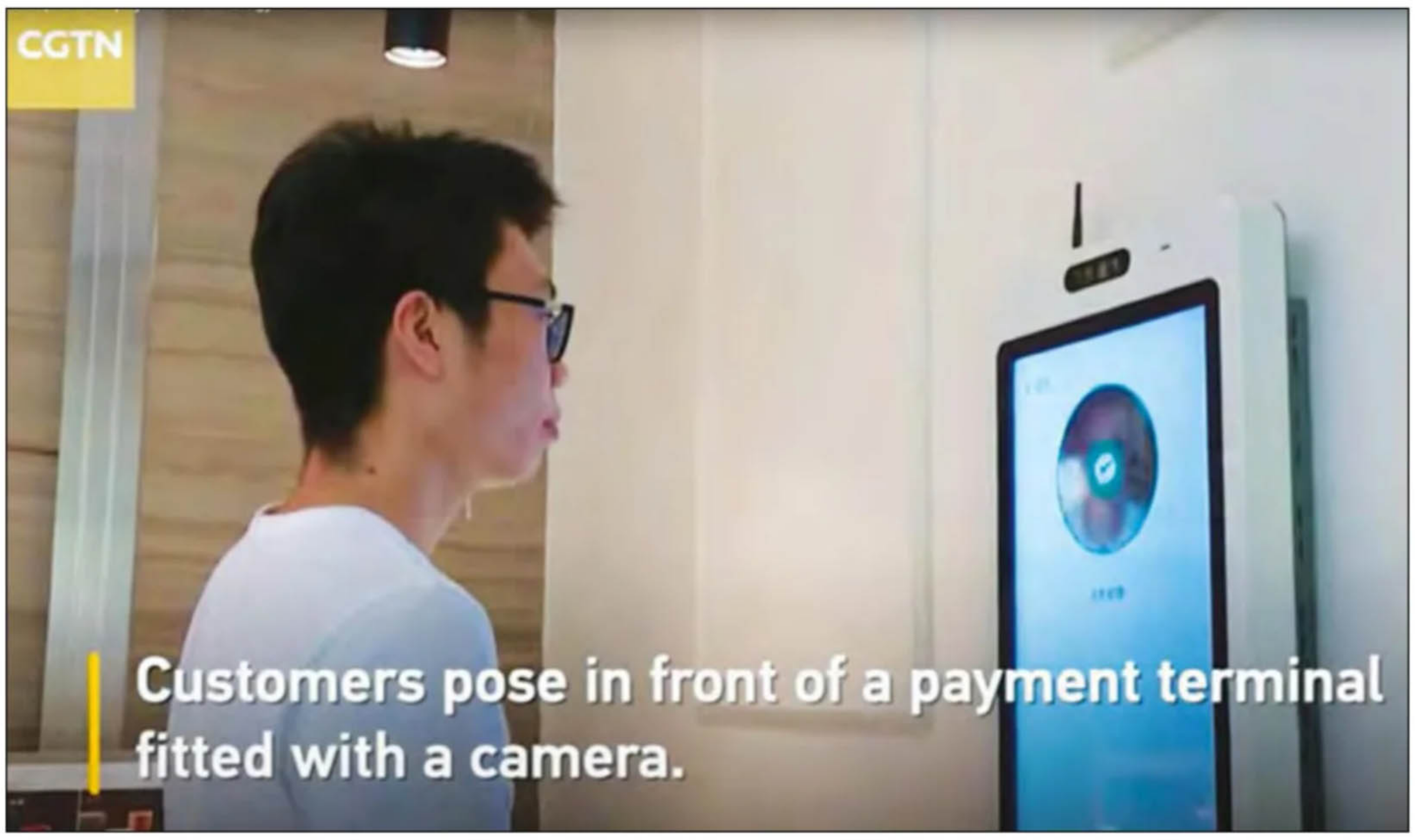
Street trials in London of facial recognition scanners stirred up some controversy over privacy last year.

include Moscow, Singapore and Baghdad. Campaign group Big Brother Watch is against using FRT in public, and for now it seems that FRT will be confined to scanning for miscreants at specific places or events.

At the other end of the scale, in China the use of facial recognition payment (FRP) to pay for things is said to be very widespread. In a report by Hanna Hua for *Retail Week*, she writes that when she re-visited China, she found facial recognition everywhere and one smile at an FRP scanner was all it took to complete a store transaction. Few credit card terminals or Apple Pay systems were seen, so no mobile device was needed to 'pay by face'. The scanner links to an e-wallet managed by Ali Pay or WeChatPay, which in turn links to a bank account. Any e-wallet credit balances earn interest (PayPal, take note). There are said to be half a billion users of FRP in China, and face ID systems are also routinely used for age verification or at police stations, banks and railway stations. Today's Internet generation would probably think FRP is a great idea, but those who value their privacy more would doubtless recoil from the suggestion.


CGTN
Customers pose in front of a payment terminal fitted with a camera.

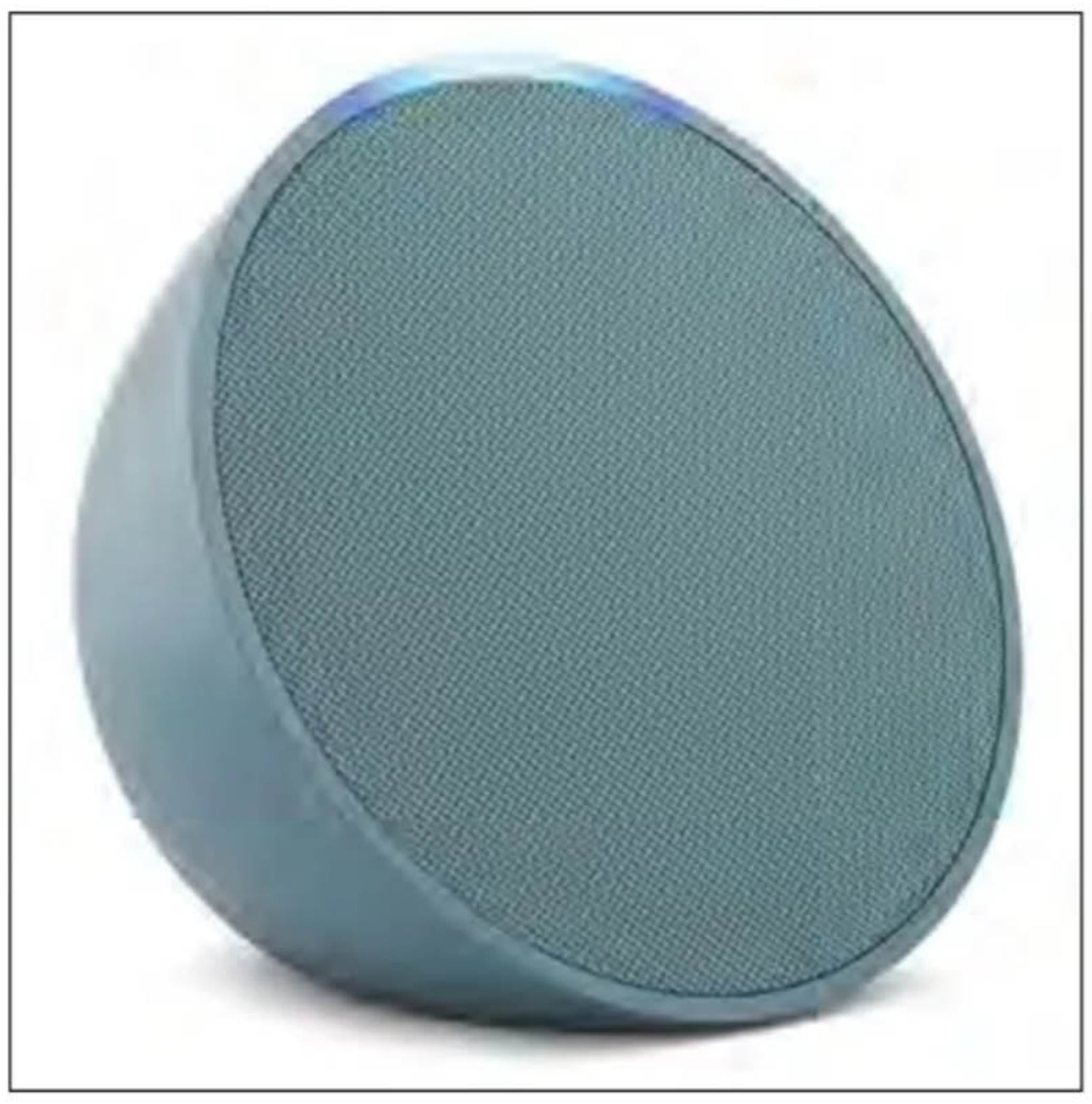
'Pay by face' uses facial recognition scanners linked to an e-wallet, and is commonplace in China. (China Global TV/ YouTube)

There's an app for that

Countless gadgets and appliances now depend on network or Bluetooth connectivity, and here at home I don't have to look far for examples: my 'smart' bathroom scales made by Etekcity will 'echo' signals around one's body mass and send to my tablet no less than 16 rather depressing statistics. Online guidance sourced from the American College of Cardiology then pops up, in an effort to give the Chinese app some credibility, though of course it's no substitute for a personal medical assessment.

Many IoT devices can utilise AI to help manage your home, such as TP-Link's Tapo and Kasa ranges, and hands-free voice control can be a boon. Using 'skills' on Amazon or Google smart speakers is an easy way of controlling sockets or lights using voice commands, an idea that we've quickly become used to. Smart speakers and displays now appear in many homes, and Amazon recently launched the latest version of their smart speaker, called the Echo Pop. It's priced at a hefty £45, although I snapped one up for an introductory price of just £18. It works very well and, unlike other brands, is guaranteed to be updated by Amazon for four more years once sales are discontinued.

Having 'apps for everything' suits today's Internet generation, but something that always attracts my ire are online posts from users who exclaim that apps are 'dead easy' and 'anyone can use them'. As if to rub it in, they add that 'no-one ever uses cash' anymore because everyone uses contactless payments instead. None of this is true when older or less well-off folks are concerned: they may not have the budget, confidence, dexterity or eyesight to run a pricey smartphone full of apps, or even if they have, they may be happy with the status quo and not want to re-learn ways of doing things that have worked perfectly well for decades.



Echo Pop is Amazon's latest version of their smart speaker. Watch out for Black Friday sales later this year.

In another nudge towards going cashless, it's claimed that some businesses are being deterred from handling or storing cash, otherwise their insurance premiums and bank charges become unaffordable. By adopting digital transactions instead, one counterargument goes, the state and financial institutions could track and ultimately control all our activity. We are not there yet, but these things tend to sneak up on us without anyone noticing until it's too late.

The digital Britcoin

Readers might have noticed that I've always steered completely clear of cryptocurrencies, Bitcoins (BTC), Ether (ETH) and the like, partly because grappling with these digital currencies goes beyond the remit of my old accountancy qualification. Some 10% of UK adults hold or have held cryptoassets, according to HM Revenue & Customs. Using cryptocurrencies is for the technically savvy (and wary) and involves engaging with privately run, volatile high-risk transactions that are 'unbacked', meaning there are no financial or physical assets behind them, let alone any form of stress-testing or regulation.

A recent cross-party UK Government committee stated that, given their price volatility and the risk of losses, trading in 'unbacked' crypto more closely

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Ten shillings
10
SHILLINGS
LONDON for the Govr. and Compa. of the BANK of ENGLAND
J. S. Fforde Chief Cashier
24W 358744

An old Sterling note can always be cashed in at the Bank of England – even a 10-shilling pre-decimal specimen. The Bank will only give you 50p for it, but you could easily get ten times that on eBay. However, that's not such a great deal when you realise 10 shillings in 1969, the year this note was withdrawn, was worth the equivalent of £7 in today's money: **https://bit.ly/pe-oct23-inf**

resembles gambling than a financial service, and should be regulated as such. However, the government disagrees, and intends to 'tame' retail crypto transactions for mainstream use by regulating them as financial services.

For now, the Bank of England and HM Treasury are looking at creating a Central Bank Digital Currency (CBDC) or a 'digital pound'. It is known that Britain's current Prime Minister Rishi Sunak is a 'Treasury man' and is all in favour of having a digital currency, perhaps even a 'Britcoin'. The digital pound would see consumers owning a 'digital wallet' into which digital currency could be paid from a bank account. The Bank of England claims that it would exist alongside, and be easily exchangeable with, cash and bank deposits.

Other examples of digital wallets are payments systems managed by PayPal, Google Pay and Apple Pay; consumers link their digital wallets to their current (cheque) accounts, as well as their debit and credit cards. The payment system then manages the transaction, charging the vendor (merchant) a small percentage fee. In a 2022 YouGov survey for the Bank of England, 22% of SMEs (small-medium enterprises) accepted PayPal, but only 3% cited PayPal as a preferred payment method, while 7% still preferred cash! Google Pay works well on a mobile phone and I like the fact that Google Pay and Apple Pay withhold your charge card number from the merchant. The Bank of England is now mulling over the idea of creating a regulated UK digital currency 'in due course', so presumably it won't happen any time soon.

Cashing in again

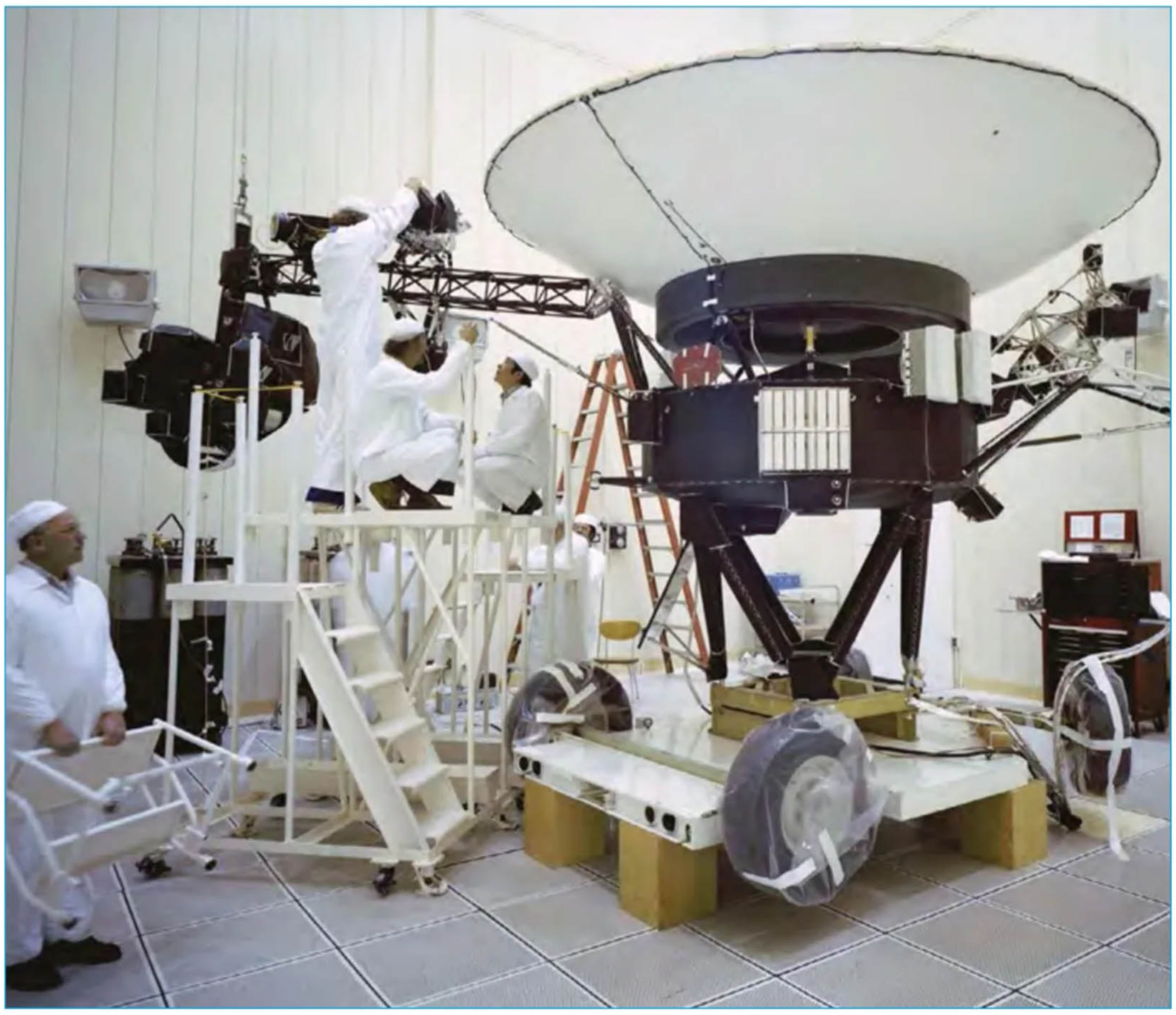
Meanwhile, back on the subject of good old-fashioned cash, some UK readers might like to be reminded that old paper bank notes are no longer legal tender, having been replaced by polymer (plastic) notes from 2016, something that an American reader had never heard of, and the Federal Reserve was steering well clear of too. Out of interest, America's National Cotton Council reports that US paper currency is actually printed on 75% cotton and 25% linen and there are 454 bills in a pound (weight, or 0.454kg) of currency.

British bank notes are effectively cast-iron IOUs that carry the statement 'I promise to pay the bearer on demand the sum of...' Some UK banks will still accept old, withdrawn paper notes and pay them into your account, otherwise they can only be cashed in at the Bank of England in London (the position in Scotland differs), which guarantees to pay against any bank notes ever circulated. The Bank of England offers a mail-in postal form at: **https://bit.ly/pe-oct23-boe**

As it happens, I had a decent bundle of old £20 and £10 bank notes stashed away, but I'd forgotten that paper notes had been withdrawn. My travails started by visiting my bank 25 miles away, because all my local branches had disappeared, a malaise blamed on the uptake of online banking. Even in this large branch, no human 'teller' service was available – no hope paying the cash in over the counter, then. The nearest (and only) counter service was in a major city branch, 40 miles away. Fortunately, a helpful banking floor worker pointed me to a paying-in machine instead, which rustled through the old £20s with impressive speed, with my debit card being used to credit my account instantly. Cheques can be scanned and paid in automatically using another machine, though the last time I tried one, it swallowed a substantial cheque before losing it and rebooting into Windows XP.

I then found that the machine was incompatible with my old £10 notes. I could either take them to London and queue up at the Bank of England, or I could risk posting them off with a form and photo ID, which is what I've done. Assuming all goes well, the Bank states that it may take 'at least 90 days' to swap my wad of paper £10 notes for real money. That's progress for you!

Clearly, cash is becoming anathema to all parts of the financial sector, including HM Treasury and tax authorities everywhere. Pushing back against this relentless drive towards digital currency and cashless transactions, the UK TV news channel GB News recently launched an online e-petition headed 'Don't Kill Cash', claiming that five million people still rely on it, adding that there are 'strong vested interests pushing for cash to be replaced by debit and credit cards'. They hoped to reach 100,000 signatures, the number needed for the UK Parliament to consider debating it. Remarkably, it has already reached



Not lost in space – the Voyager 2 spacecraft, seen here being worked on by NASA engineers in 1977, has travelled more than 12 billion miles from Earth. (NASA/JPL-Caltech)

308,000 signatures, and supporters can add their own name at: **https://bit.ly/pe-oct23-cash**

Incidentally, any British citizen can start a petition using the process found at: **https://petition.parliament.uk/help**

Long-distance Voyager

NASA technicians have re-established contact with Voyager 2, the plucky and venerable interstellar satellite that is now 46 years old. Launched in 1977, Voyager 2's mission was to fly by Jupiter, Saturn, Uranus and Neptune before heading out into interstellar space. It now takes 36 hours for signals to reach Voyager 2 and the answer to then return but, after a worryingly extended period of radio silence, the spacecraft has now 'phoned home' and is working normally once again. Should it ever encounter alien life, Voyager carries a 12-inch gold-plated phonograph disk containing sounds and images portraying life and culture here on Earth. The remarkable efforts of NASA to make contact with Voyager 2 are described at: **https://bit.ly/pe-oct23-nasa** and there's a treat of a website dedicated to Voyager at: **https://voyager.jpl.nasa.gov**

NASA has also re-made contact with the Ingenuity helicopter on Mars, after an unscheduled shut-down and safe landing (on automatic pilot) in July. Ingenuity has now flown 54 missions (see *Net Work*, August 2023).

Some encouraging news comes from Virgin Galactic, which successfully joined the space tourism industry by taking three passengers to the edge of space in August. The three, including the first mother and daughter to fly into space, flew in the VSS Unity and travelled some 88km in a journey lasting 16 minutes.

Britain's BT has announced successful early trials of a satellite-based Internet link provided to a community on the island of Lundy (population 28) in the Bristol Channel. The Internet feed was supplied by OneWeb, the LEO satellite network operator that is expected to merge with France's Eutelsat. A little more on Lundy here: **https://bit.ly/pe-oct23-lundy**

At the other end of the country, Saxa Vord, the UK's most northerly spaceport, is gearing up for its first vertical rocket launch later this year, subject to licensing approvals. Demand for launch slots far exceeds global supply, I learned, but as part of its steep learning curve the Saxa Vord team cheerfully exclaims that they won't mind if its first rocket actually blows up. Meantime, Scotland-based Skyrora is trialling its 3D-printed rocket engine and is also doing excellent work in enthusing youngsters – tomorrow's engineers – about space technology and engineering.

China has launched Lingxi 03, a flat blade of a satellite fitted with a flexible solar array that marks the country's next step in building its own mega constellation of LEO satellites to carry broadband and 5G services. Half a dozen test satellites were launched last year, and the Chinese satellites are also reportedly equipped to take photos and video.

Connected by OneWeb
Intellian

BT and OneWeb, in partnership with the UK government, are now delivering high-speed, low-latency internet connectivity to Lundy Island, North Devon.

Outside interference

Following my item last month on mains adaptors and DC connectors, my thanks go to long-time reader and friend of *PE*, Godfrey Manning (G4GLM) who asks: 'Is your "Zolt" PSU linear or switching? You can usually tell immediately from the weight when you pick it up. As a Radio Amateur, I'm reluctant to buy switch-mode PSUs because of the interference to the weak signals I'm listening for (and I'm already struggling with MW/AM broadcasts for this reason). Regards (or "73" in Morse Code).'

I've some old linear regulated mains adaptors which weigh a ton in comparison with modern SMPSUs like the one I mentioned, due to their bulky transformer. Switched-mode ones are compact and lightweight, which also makes them cheaper and easier to ship. I can understand the issue with RFI: a few days ago, when updating our website, I noticed my mouse pointer was shaking violently on screen, as if I had a case of *delirium tremens*. I tried updating Windows drivers and other ideas, but an hour later I discovered the problem was actually with my graphics tablet, or rather RFI from my desk light, which was interfering with the tablet's radio signals. By moving the lamp a foot or two (0.5m) away, the mouse pointer stopped shaking! This is a handy reminder that LED-based or other 'simple' low-voltage lighting often involves noisy

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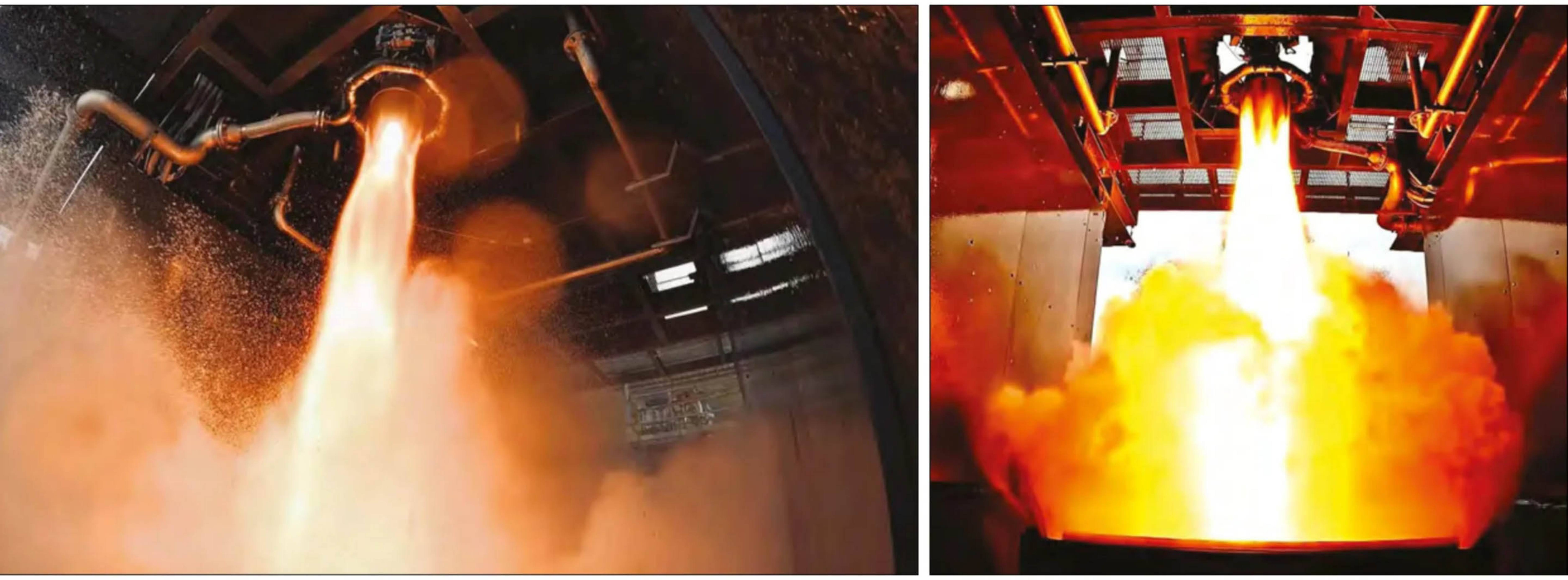

Skyrora tests its new 3D-printed orbital engine in readiness for commercial launches. The use of 3D printing reportedly cut production times by 66% and costs by 20%.

SMPSUs. And even if it doesn't, home wiring can act as excellent conduits for noise generated elsewhere, which could then be transmitted to a lamp or any other mains-powered device without adequate RF filtering/shielding.

Last, surfing around an electronics group recently, I saw the topic of fake CE marks on Chinese goods had once again cropped up but, worryingly, some people still bought into the fallacy that a fake CE mark is an authentic logo meaning 'China Export', as though it's a 'real' thing. I covered this topic back in the October 2021 issue: the only difference between genuine CE logos and fake ones was that the bogus 'C' and 'E' letters were closer together. Unfortunately, Google returns search results for important-looking but misleading websites that should really be taken down. Don't be taken in – you can learn more at: **https://bit.ly/pe-oct23-ce**

That's all for this month's *Net Work*. Remember the above links will be ready-made for you to click on by visiting the *Net Work* blog at: **www.electronpublishing.com**

The author can be reached at:
alan@epemag.net

Teach-In 8 CD-ROM
Exploring the Arduino

This CD-ROM version of the exciting and popular *Teach-In 8* series has been designed for electronics enthusiasts who want to get to grips with the inexpensive, immensely popular Arduino microcontroller, as well as coding enthusiasts who want to explore hardware and interfacing. *Teach-In 8* provides a one-stop source of ideas and practical information.

The Arduino offers a remarkably effective platform for developing a huge variety of projects; from operating a set of Christmas tree lights to remotely controlling a robotic vehicle wirelessly or via the Internet. *Teach-In 8* is based around a series of practical projects with plenty of information for customisation. The projects can be combined together in many different ways in order to build more complex systems that can be used to solve a wide variety of home automation and environmental monitoring problems. The series includes topics such as RF technology, wireless networking and remote web access.

PLUS: PICs and the PICkit 3 – A beginners guide
The CD-ROM also includes a bonus – an extra 12-part series based around the popular PIC microcontroller, explaining how to build PIC-based systems.

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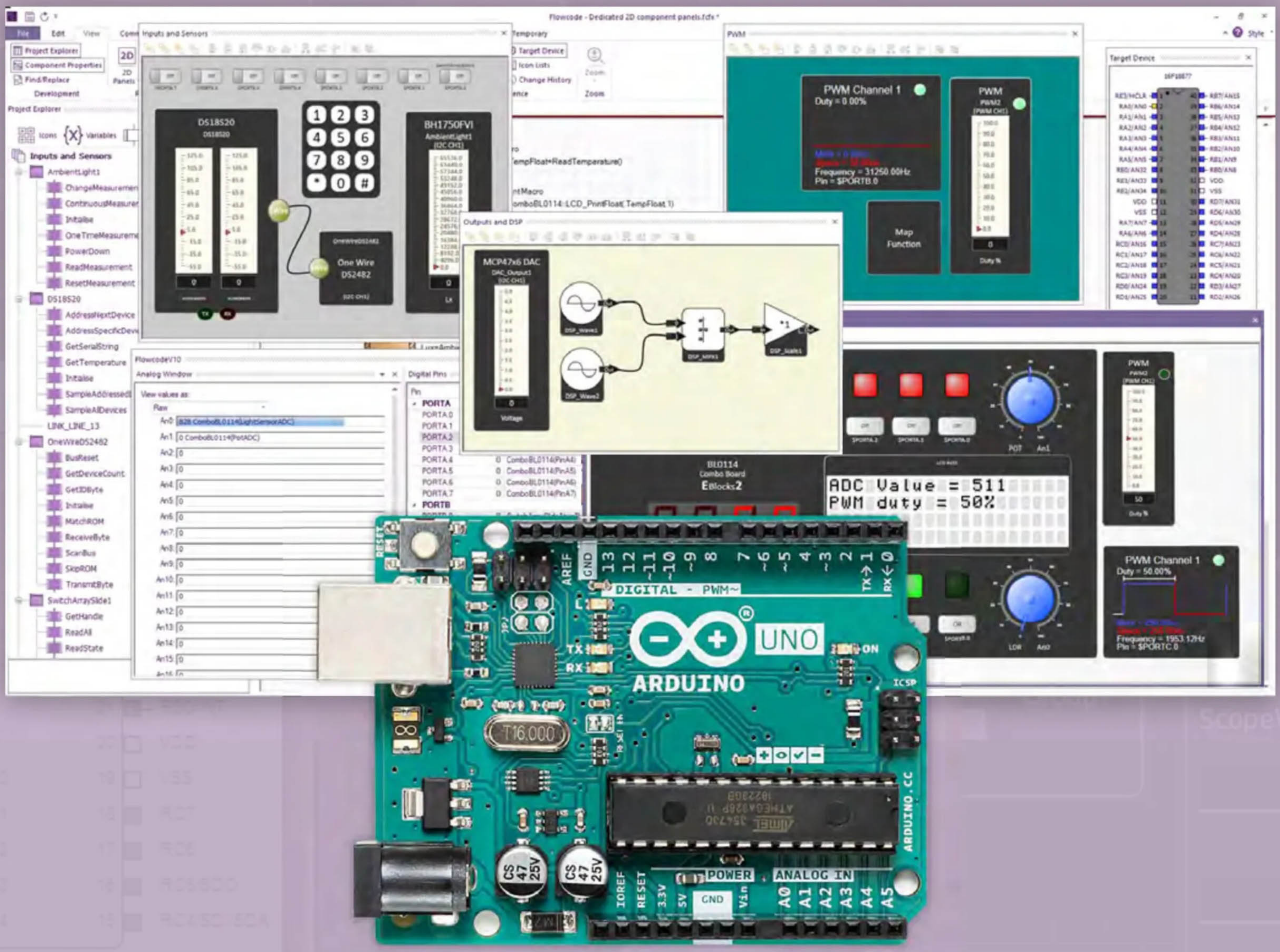

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AUTOMATIC LEVEL CROSSING AND SEMAPHORE CONTROL

WITH ‘CHUFF’ AND WHISTLE SOUNDS

This project combines the *Model Railway Level Crossing* and *Semaphore Signal* projects with a *Li’l Pulser Mk.2* train controller to automate a model railway layout. It also adds chuffing and whistle sounds to make it as realistic as possible.

BY LES KERR

The Automatic Train Controller makes your train pull up to the *Semaphore Signal*, triggering the *Level Crossing*, then proceed through the crossing when safe, all automatically and with accompanying sound effects.

It made sense to integrate this with my *Li’l Pulser Mk.2 Model Train Controller*. All of the projects required to build the *Automatic Train Controller* are listed in the opposite panel; except the *Carriage Lights* which are optional.

To make it more realistic, I added two sound modules, one to produce steam whistle sounds and another to add engine chuff noises. You can see a video of all these devices operating in concert at: **https://bit.ly/pe-oct23-loco**

In that video, the *Semaphore Signal* goes up to alert the train to stop, then the train slows down and stops at the *Signal*. The barriers on the *Level Crossing* close, the bells sound and lights flash, then the *Signal* goes down and after a delay, the train moves off slowly. As the train approaches the *Level Crossing*, the whistle sounds. Once the train has passed through the *Crossing*, it resets.

An elegant feature of the *Li’l Pulser Train Controller* is its built-in inertia simulator, which means that the train slows down like its full-size version and moves off slowly. It does this simply by charging and discharging a capacitor.

In case you only want to make the chuff sound module and not the train controller, I have split the design up into two separate circuits and PCBs.

Automatic train control

The overall arrangement of the *Train Controller* is shown in the block diagram, Fig.1. It still allows you to operate the *Level Crossing* and *Semaphore Signals* manually by associated toggle switches. Double-pole, double-throw (DPDT) toggle switch S1 switches between automatic and manual control.

In manual mode, the *Li’l Pulser Train Controller* operates as usual. So that the *Crossing* and *Signal* can be used in each mode, we use diode OR gates on their control inputs. This means that the automatic control board drives the control inputs of these modules when it is selected, while the manual switches drive them when the *Automatic Controller* is disabled. A reed switch under the track is used to start the automatic process.

In automatic mode, a magnet on the engine closes this reed switch as

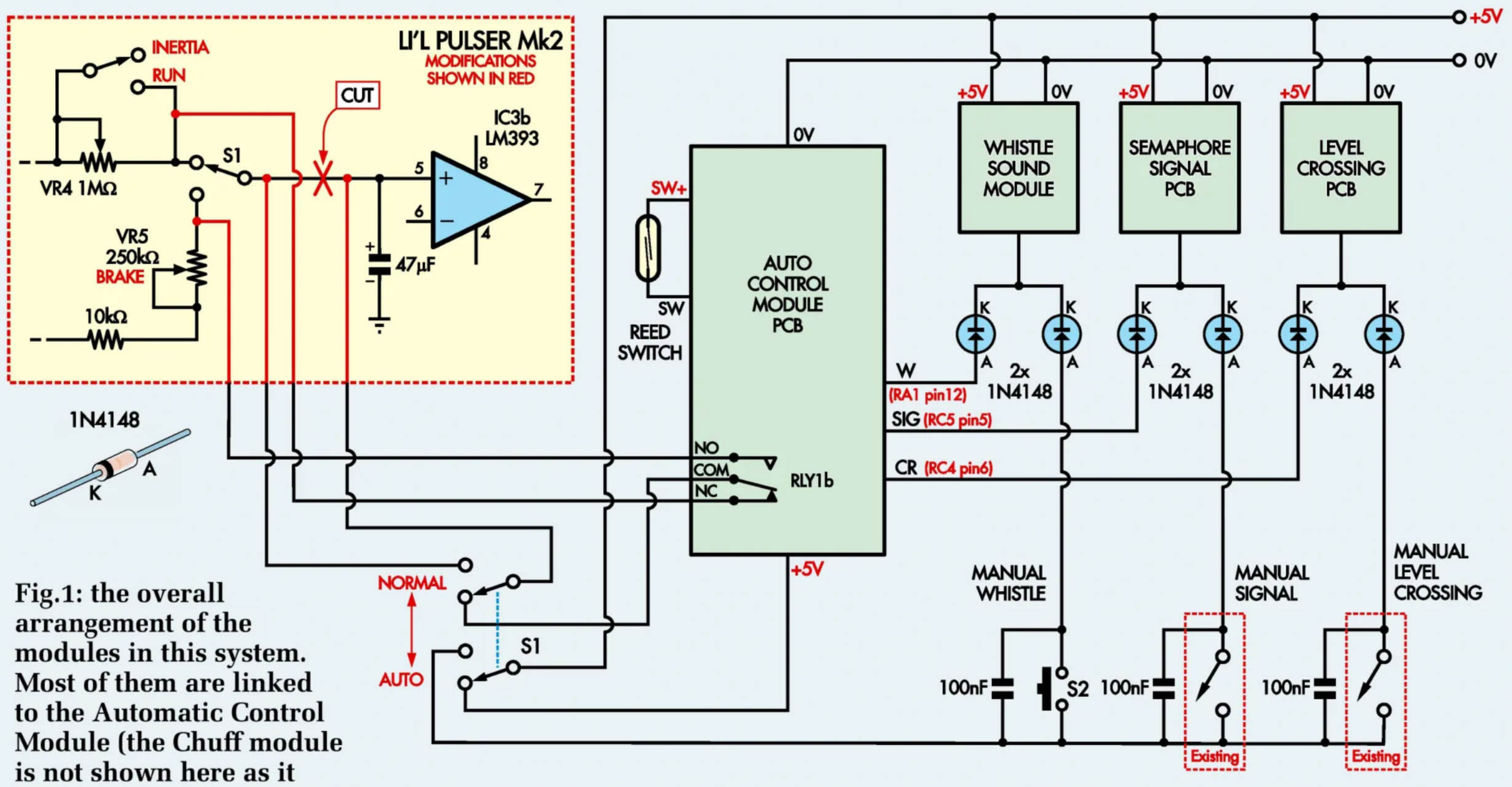

LI'L PULSER Mk2
MODIFICATIONS SHOWN IN RED
INERTIA
RUN
CUT
IC3b LM393
S1
VR4 1MΩ
VR5 250kΩ
BRAKE
10kΩ
47µF
1N4148
A
K
SW+
REED SWITCH
SW
0V
AUTO CONTROL MODULE PCB
W
(RA1 pin12)
SIG (RC5 pin5)
CR (RC4 pin6)
NO
COM
NC
RLY1b
+5V
+5V
0V
WHISTLE SOUND MODULE
SEMAPHORE SIGNAL PCB
LEVEL CROSSING PCB
2x 1N4148
NORMAL
AUTO
S1
MANUAL WHISTLE
MANUAL SIGNAL
MANUAL LEVEL CROSSING
100nF
S2
Existing

Fig.1: the overall arrangement of the modules in this system. Most of them are linked to the Automatic Control Module (the Chuff module is not shown here as it operates independently). The Control Module can start or stop the train by using RLY1 to change how the Li'l Pulser operates. When required, it also triggers the Steam Whistle, Semaphore Signal and Level Crossing modules.

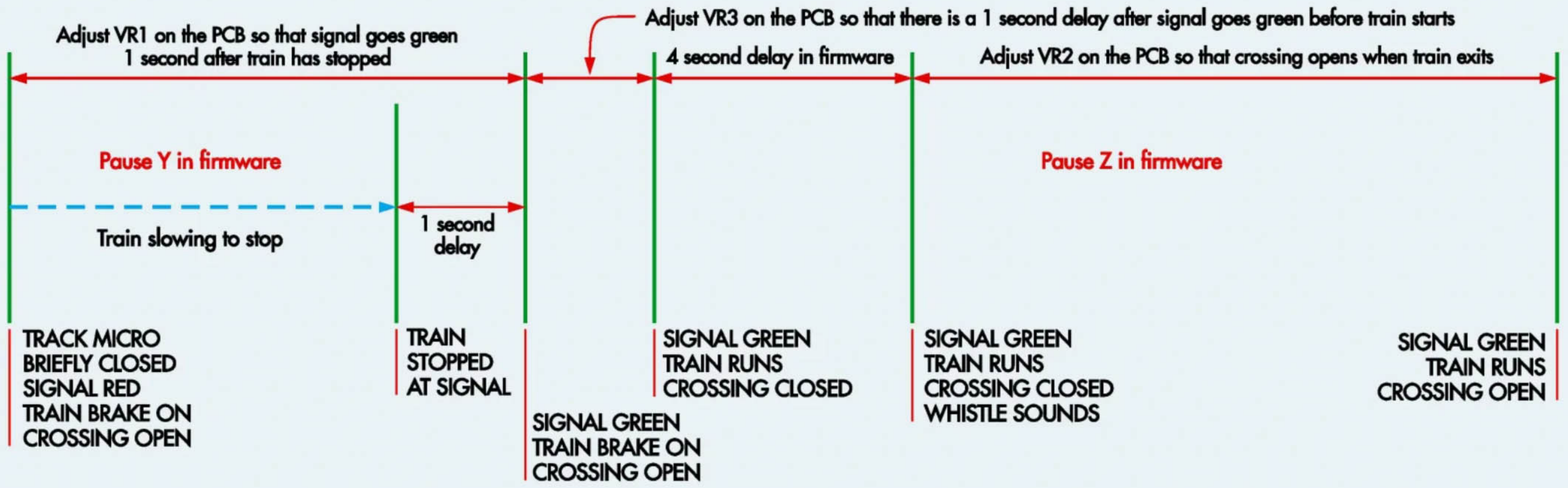

Adjust VR1 on the PCB so that signal goes green 1 second after train has stopped
Adjust VR3 on the PCB so that there is a 1 second delay after signal goes green before train starts
4 second delay in firmware
Adjust VR2 on the PCB so that crossing opens when train exits
Pause Y in firmware
Pause Z in firmware
Train slowing to stop
1 second delay
TRACK MICRO BRIEFLY CLOSED SIGNAL RED TRAIN BRAKE ON CROSSING OPEN
TRAIN STOPPED AT SIGNAL
SIGNAL GREEN TRAIN BRAKE ON CROSSING OPEN
SIGNAL GREEN TRAIN RUNS CROSSING CLOSED
SIGNAL GREEN TRAIN RUNS CROSSING CLOSED WHISTLE SOUNDS
SIGNAL GREEN TRAIN RUNS CROSSING OPEN

Fig.2: this timing diagram shows the sequence of events. If this is unclear, see: https://bit.ly/pe-oct23-loco Three of the delays are adjustable using trimpots VR1-VR3 on the Control Module.

the engine passes, starting the timing sequence shown in Fig.2. Timer 1 (adjustable from half a second to 10 seconds) starts, the *Signal* goes up and the relay on the PCB operates, closing contacts RLY1b.

The closure of those contacts connects the 250kΩ brake potentiometer to the 47µF capacitor on the positive input of IC3b in the *Li'l Pulser Train Controller*, stopping the train. At the end of Timer 1's period, the *Signal* goes down. Timer 1 is adjusted so that the *Signal* goes down one second after the train has stopped.

Timer 3 (0.5 to 10 seconds) is adjusted for the driver's reaction time to start the train. I set mine to one second. When Timer 3 expires, the *Level Crossing* closes and the relay is de-energised, opening contacts RLY1b. The 47µF capacitor is now connected to the 1MΩ inertia pot, causing the train to move off slowly as the capacitor charges.

Then there is a fixed four-second delay before a signal is sent to operate the whistle in the sound module. The train runs on through the *Level Crossing* and then, when the train has passed and Timer 2 expires, the *Level Crossing* opens.

Control circuit details

The circuit of the *Auto Control Module* black box from Fig.1 is shown in Fig.3. It is pretty straightforward since most of the functions are provided by the PIC16F1455 microcontroller (IC1).

When the reed switch closes, the RC1 input (pin 9) of IC1 that is usually held low by the 10kΩ resistor is pulled high. This triggers the software into action. It uses three identical 0.5-to-10-second timers, adjusted using trimpots VR1-VR3. The 680Ω padder resistors set the minimum voltage achievable for each pot's wiper to about 0.5V, which corresponds to half a second.

Taking Timer 1 as an example, VR1 adjusts the voltage at analogue input pin RC0 (AN4) of IC1. The 100nF capacitor filters out any ripple or interference, so there is a steady voltage at that pin. The microcontroller's internal analogue-to-digital converter (ADC) is used to turn this voltage into a number to calculate the time delay. The other two timers are similar, using VR2/RC2/AN6 and VR3/RA4/AN3.

Projects needed to build the Automatic Train Controller

Li'l Pulser Mk.2 Model Train Controller	*July 2014*
Model Railway Level Crossing	*July 2022*
Model Railway Semaphore Signal	*March 2023*
Model Railway Carriage Lights	*November 2022 (optional)*

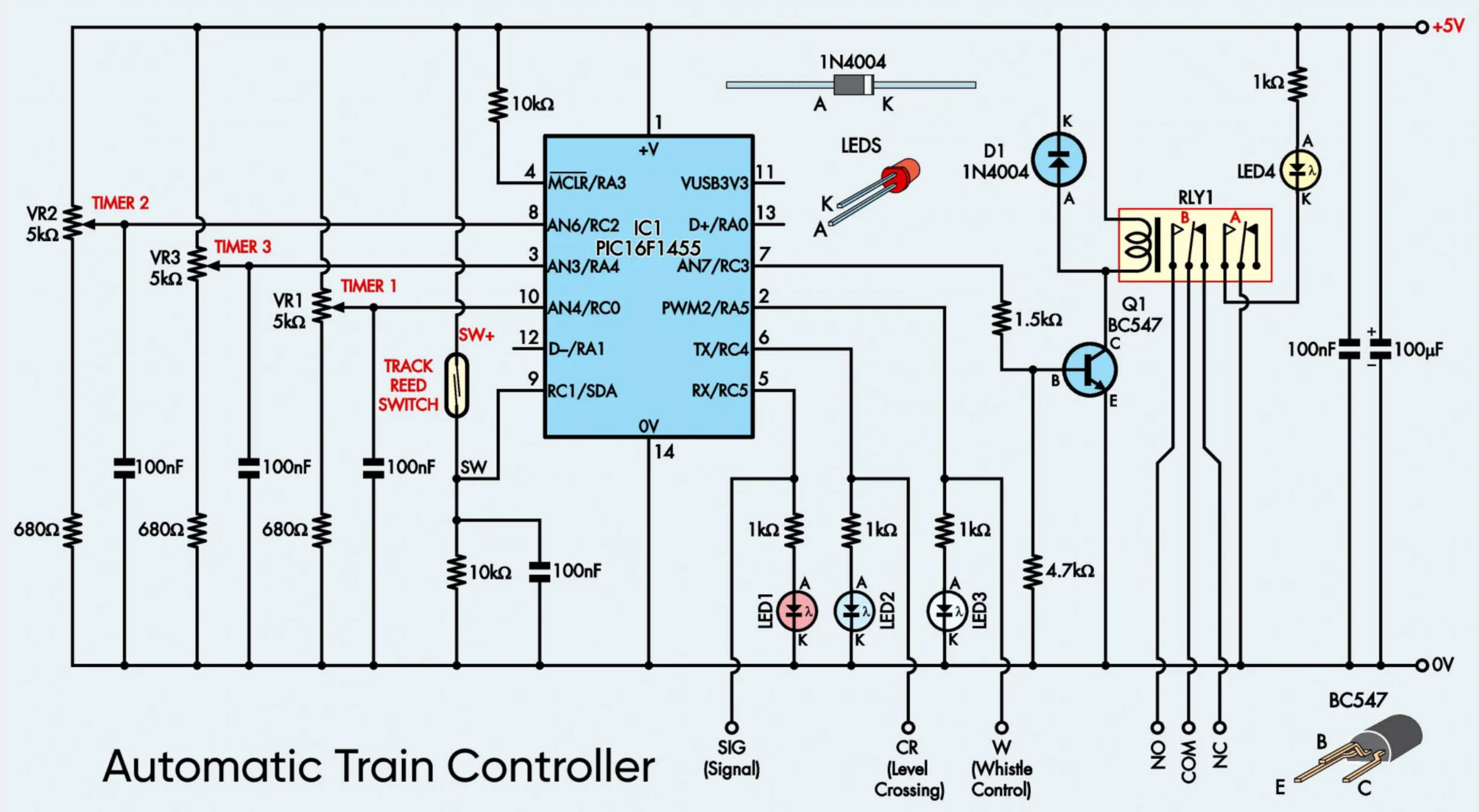


Fig.3: the Control Module is based around microcontroller IC1, which uses internal timers to generate the control signals at RA5, RC4 and RC5 when appropriate. Those timer durations are adjusted using trimpots VR1-VR3 that apply varying DC voltages to the AN4, AN6 and AN3 analogue inputs. The closure of the reed switch at pin 9 of IC1 (the RC1 input) starts the whole sequence.

IC1's RC3 digital output (pin 7) is used to switch NPN transistor Q1 which controls the coil of relay RLY1. IN4004 diode D1 protects the transistor from the back-EMF generated by the coil's inductance when the relay switches off. Contact RLY1a switches yellow LED4 while contacts RLY1b are used to change the *Li'l Pulser* between the brake and run modes.

IC1's digital outputs (RA5, RC4 and RC5) are used to produce the three control signals to trigger the *Semaphore Signal*, *Level Crossing* and *Whistle Sound* modules, respectively. These signals are also applied to the LEDs (LED1-LED3) via 1kΩ current-limiting resistors so you can easily see when different modules are being triggered.

Output RC4 (pin 6), when high, closes the *Level Crossing* and switches on blue LED2. Similarly, when output RC5 goes high (pin 5), the *Signal* goes up and red LED1 lights. Then, when output RA5 goes high (pin 2), the whistle module is triggered and white LED3 flashes for 200ms.

The only other components are the 10kΩ pull-up resistor at the $\overline{\text{MCLR}}$ input of IC1 (pin 4), to prevent spurious resets, and the 100nF and 100μF supply bypass capacitors, mainly for the benefit of IC1.

Chuff Sound circuit details

My design for the 'Chuffer' circuit which produces the 'chuff' sound of a steam locomotive is based on ideas developed by Greg Hunter. The voltage supplied to the locomotive is sensed to vary the chuff rate. The higher the voltage, the faster the 'chuffs'. When the locomotive is stationary (no track voltage), it produces a 'panting' sound that is like an engine compressor running.

The resulting circuit is shown in Fig.4. It is separate from the other modules; while they are great in combination, it can also be used as a standalone device. The voltage from the rails is applied to a bridge rectifier, and the resulting DC is reduced by an adjustable resistive divider, clamped to a safe level by an LM4040 IC acting like a 5V zener diode and filtered by a 10μF electrolytic capacitor.

The result is a 0-5V signal applied to the GP2 analogue input (pin 5) of PIC12F675 microcontroller IC1 that, when VR4 is adjusted correctly, lets it measure at what speed the train is currently moving. VR4 is adjusted for 3.3V at its wiper when the train is running at a realistic maximum speed. Depending on the make of your controller, you might have to change the 15kΩ resistor value to achieve that.

Note that this will not work with a DCC system because those systems do not vary the voltage across the tracks – instead, they send digital signals to the locomotives.

Microcontroller IC2 and LM386 audio amplifier IC3 are powered from a separate 5V DC regulated supply. This 5V supply must be floating with respect to the track supply; one can be earthed, or the other, but not both. Otherwise, the supplies will be shorted out via the bridge rectifier. A separate 5V DC regulated plugpack is a good option here.

The voltage applied to the GP2 input of IC1 is converted to an 8-bit digital number (0-255) by IC1's internal ADC. This number is proportional to the locomotive speed. A nice feature of this PIC is its internal square-wave oscillator that can be programmed to produce 127 tones and 128 notes of white noise.

To simulate the hissing noise of the engine, we use a couple of the white noise outputs. The output is switched on and off depending on the ADC voltage, so we get more chuff pulses as the train accelerates. The reverse happens when the train slows down. When the train is stopped, the panting sound is generated by another white noise channel with the pulses separated by a few milliseconds.

These waveforms are applied to the GP1 digital output (pin 6), which is AC-coupled to the input of IC3 via a variable attenuator. In this configuration, IC3 has a gain of 20 and can deliver up to 300mW into the 8Ω speaker. The 1kΩ potentiometer VR5 determines the output volume.

I used a 57mm diameter speaker with a 100mm square white card

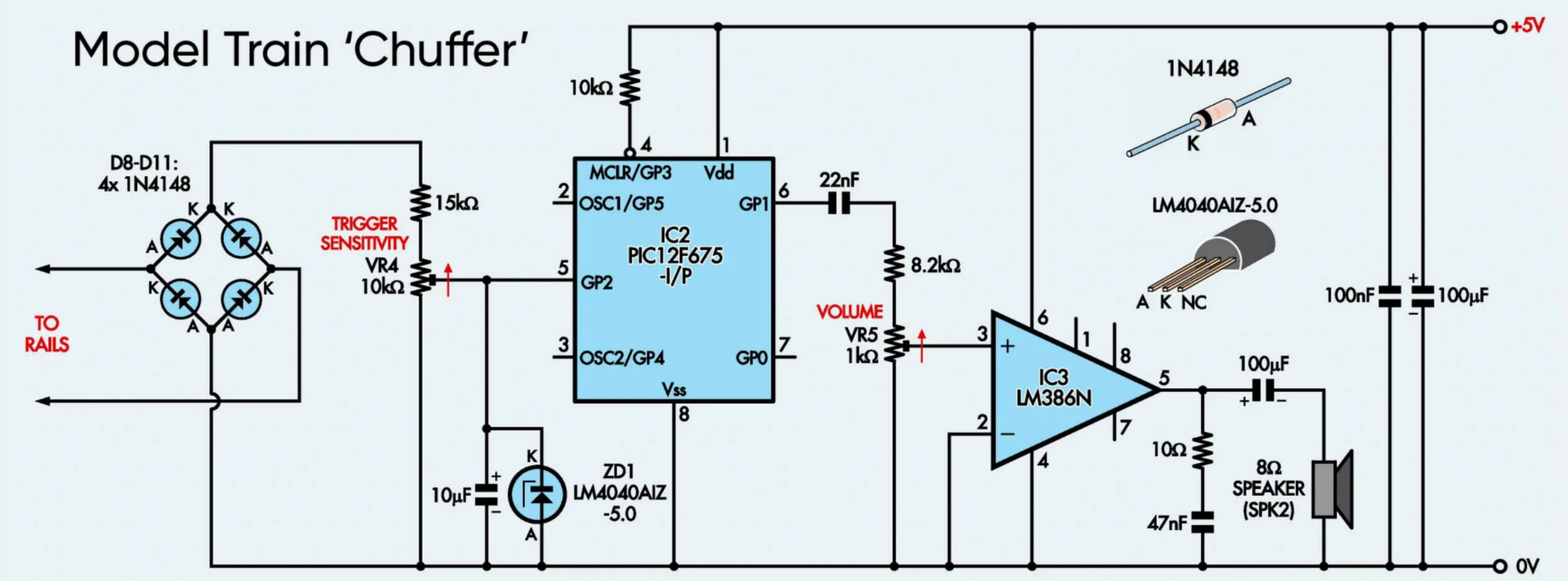


Fig.4: the Chuff Sound Module is pleasingly simple. The voltage across the rails is rectified, filtered, reduced and then applied to the GP2 analogue input of IC2 so it can sense the train speed. It produces the panting or chuff sounds at its pin 6 digital output (GP1), and these signals are fed to audio amplifier IC3 and ultimately, the speaker.

mounted on its back to stop the reflected sound, which resulted in just the right amount of bass to match my Peckett tank engine. Depending on what you are running, you may have to experiment to get the optimal sound for your engine. Putting the speaker in a box will increase the bass.

Construction

The first build step is to assemble the PCB module(s). For the *Li'l Pulser*, *Semaphore* and *Level Crossing* modules, see the instructions in the July 2014, March 2023 and July 2022 issues respectively.

The *Train Control* module is built on a single-sided PCB, coded 09109221 that measures 50 x 51mm and which is available from the *PE PCB Service*. The necessary parts are in the parts list, and the component layout (overlay) is shown in Fig.5. While the PCB is a single-sided design, if you buy it from our online shop, we will supply a double-sided board that will save you having to fit the two wire links.

Start by fitting the PCB pins, followed by the IC and relay sockets. Take care to orient the sockets correctly. There is no onboard programming header, so you will need to remove the chip from the socket later if you wish to reprogram it.

Next, fit the resistors (mounted vertically), followed by the capacitors and trimmer potentiometers. The electrolytic capacitors are polarised (longer lead to + pad), but the ceramic capacitors are not. If you have a single-sided PCB, fit the two wire links now using resistor lead off-cuts.

Next, install the diode, LEDs and transistor. They all need to go in the right way round; check Fig.5 if you are unsure. Then plug in the relay, oriented as shown.

Don't plug in the PIC microcontroller yet. If you have a blank PIC then you will need to program it yourself; you can download the HEX file from the October 2023 page of the *PE* website at: **https://bit.ly/pe-downloads**

You will need a PICkit 4, Snap programmer or similar to load the file, along with a socket adaptor for the PIC16F1455 device.

PCB testing

First, inspect the board for dry solder joints and check that the diode, capacitors and sockets are inserted correctly. Connect the PCB to a 5V DC power supply, switch it on and connect the negative lead of a voltmeter to pin 14 of IC1's socket. Probe pin 1 of that socket with the positive lead and the meter should read close to +5V. If it doesn't, check the power supply and socket polarity.

Switch off power and plug in IC1, checking that it is correctly oriented, then adjust the three trimpots to their mid positions. Switch the power on and momentarily connect a wire link between the reed switch terminals, SW and SW+.

Upon doing that, the red and yellow LEDs should light. About five seconds later, the red LED should go out. After a further five or so seconds, the yellow LED should extinguish and the blue LED should light. Four seconds later, the white LED should switch on for 200ms, and in a further five or so seconds the blue LED should go out.

This shot shows off the semaphore signalling section of the project.

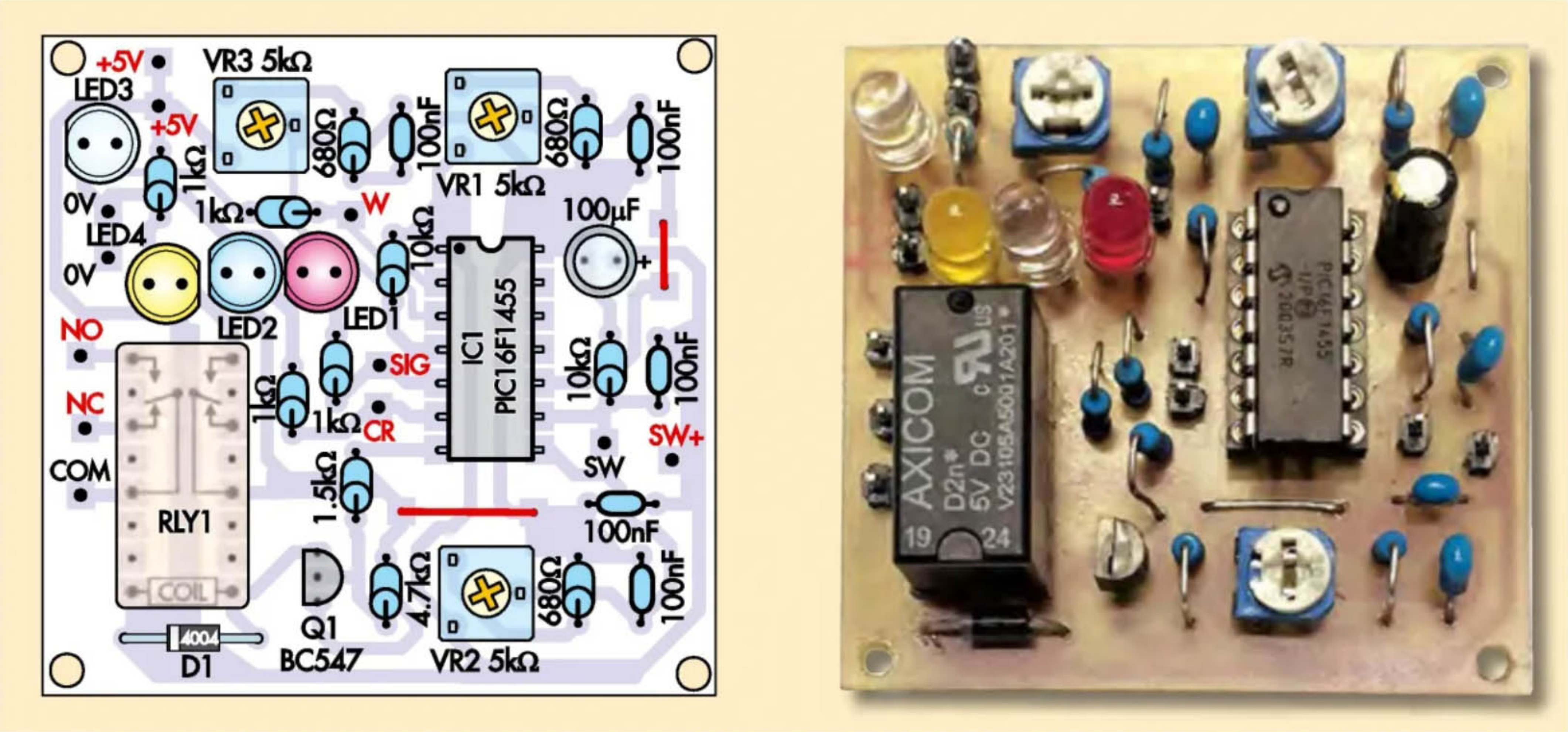


Fig.5: assemble the Control Module as shown here. It can be etched as a single-sided design, but then two wire links are needed (shown in red). They are already part of the commercially made double-sided PCBs we supply. When building it, watch the orientations of the IC, relay, diodes, transistor and electrolytic capacitors.

If that all went well, power it off and give the bottom of the PCB a coat of clear varnish to protect it from corrosion.

Whistle Sound module

My initial plan was to add the *Whistle Sound* to the *Chuff* generator, but it is difficult to produce a whistle sound electronically that covers the full range of possible locomotives. Instead, I decided to use the simple ISD1820-based sound recording and playback module. This means that you can choose and record a suitable locomotive whistle sound from the Internet.

Another advantage of this approach is that the chuff sound and the whistle sound are present simultaneously.

The first step in setting this up is to record the whistle sound onto the module. Connect the 76mm 8Ω loudspeaker (SPK1) to the green terminal block marked 'speaker', then wire a 5V DC supply between the terminals marked VCC and GND on the module.

Looking at the component side of the module with the green terminal block on the left, ensure that the two slide switches marked FT and repeat are to the left-hand side (both open). if you have the jumper-based version (pictured opposite) then the jumper positions shown highlighted in red should be suitable.

Next, find the whistle sound file you need via an Internet search. Hold the module so that the electret microphone is about 100mm from the computer's loudspeaker and set the sound to maximum volume.

Hold down the REC button on the module, then hit play on the computer. Continue holding down the record button until LED1 goes out (the maximum recording time is around 10 seconds). Now momentarily press the PLAYE button. You now should hear the recording of the whistle. If it sounds distorted, try turning the computer playback volume down and re-record it.

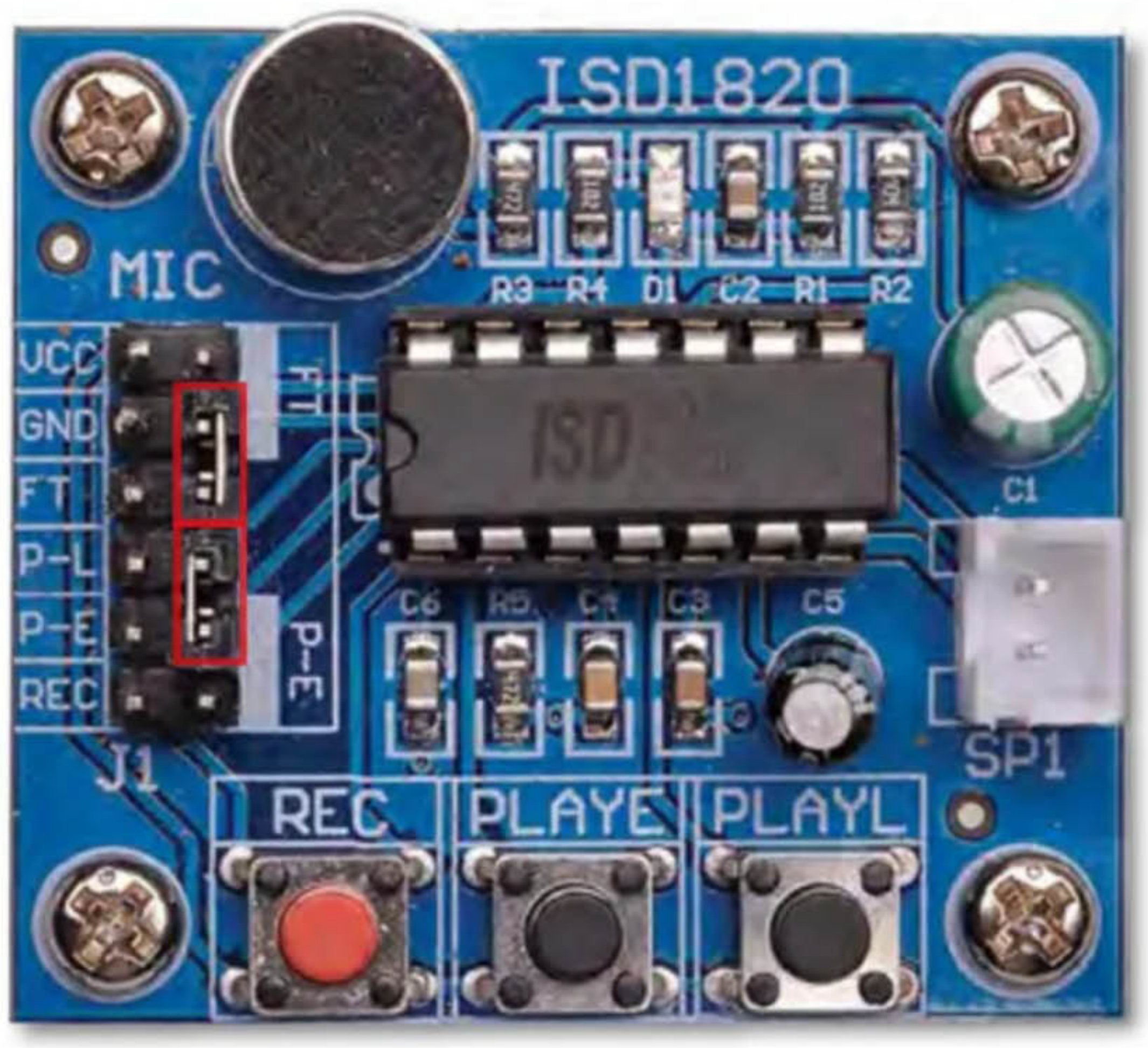
Chuff sound PCB assembly

The Chuff circuit is built on a 59 × 30mm single-sided PCB, coded 09109222 and available from the *PE PCB Service*. Refer to its overlay diagram (Fig.6) during assembly.

As mentioned earlier, it could be used independently, not just as part of the automatic system. Start assembly by fitting the PCB pins and the IC sockets, ensuring the latter are oriented correctly. Do note that just like the *Control* board, there is no provision for onboard programming of the microcontroller.

Now add the resistors, mounted vertically, followed by the capacitors; the electrolytics are polarised (the longer lead goes to the + pad), but the others aren't. Follow with the two trimmer potentiometers but don't get the two different values mixed up.

If using a single-sided board, you can fit the wire link now (which can be made from a component lead off-cut); it isn't needed for the double-sided version. Solder in the diodes next; they need to be the right way around.



Some ISD1820-based modules look a little different. However, the required connections are the same.

If using a 4.7V zener diode rather than the LM4040, solder its cathode (striped) end lead to the centre pad of the TO-92 footprint, and the other (anode) lead to the LM4040 pad closest to the edge of the board. Otherwise, if using the LM4040, mount it as shown in Fig.6.

Temporarily connect the positive of the 5V power pack to the +5V PCB pin, and the negative to 0V. Also wire in the loudspeaker as shown. At this stage, do not plug in the audio amplifier (IC3) or the PIC microprocessor (IC2).

If you have a blank microcontroller then you will now need to program it. Again, you can download the relevant HEX file from the October 2023 page of the *PE* website at: **https://bit.ly/pe-downloads**

Use a PICkit 3, PICkit 4, Snap programmer or similar to load the HEX file into the chip via a socket adaptor. We recommend you use the free Microchip MPLAB IPE software.

Testing the Chuff module

First, inspect the board for dry solder joints and check that the diodes, capacitors and sockets are inserted correctly. Switch on the power supply and connect the negative lead of a voltmeter to pin 8 of IC2's socket, with the positive lead to pin 1. The meter should read close to +5V.

If it doesn't, you have likely wired the power supply the wrong way round or the socket is reversed. Assuming it's OK, switch off the power and insert the two ICs, checking that they are correctly oriented and not swapped. Adjust both potentiometers to the mid position.

Switch the power on and you should hear a 'panting' sound coming from the speaker. Adjust VR5 so that the sound is at a comfortable level. Connect a 12V variable supply to the track inputs and slowly wind up the supply. The speaker should now emit a chuffing sound with the frequency increasing as the voltage rises. Finally, give the bottom of the PCB a coat of clear varnish to protect it from corrosion.

Wiring it up

Next, we need to determine where to place the reed switch in relation to the *Semaphore Signal*. To do this, we first have the locomotive running at a realistic speed in the normal mode and apply the brake. Measure its stopping distance and place the reed switch under and perpendicular

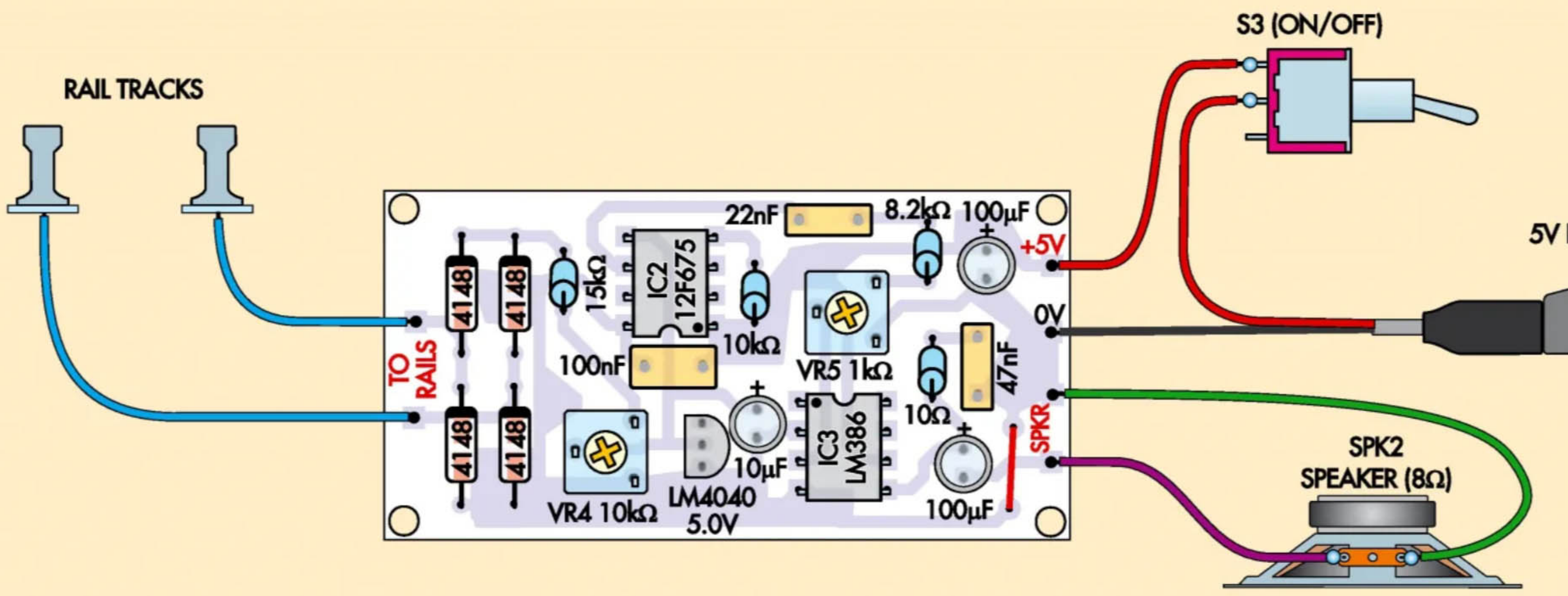


Fig.6: assembly of the Chuff Sound Module is similar to the Control Module, just simpler as there are fewer parts. The parts where polarity is critical are the diodes, ICs and electrolytic capacitors. The LM4040 is ideal, but a 4.7V zener diode can be used instead, with the cathode (striped) end to the middle pad and the other lead to the bottom-most pad.

to the rails at that distance before the *Signal*.

I set the reed switch in a groove so that its cylindrical top was level with the bottom of the rail. You may well have to experiment with this, depending on the type of engine you have and where you place the magnet within it.

Be careful not to place the magnet in direct contact with the reed switch, as this can demagnetise it, causing it to fail.

I built the *Li'l Pulser Mk2 Train Controller* in a larger enclosure than originally specified (Jaycar HB6128 ABS), measuring 171 × 121 × 56mm. This was so that I would have more room to mount the *Automatic Control* PCB, its corresponding on/off switch, the manual *Whistle* push button, the manual *Signal* toggle switch and the manual *Crossing* toggle switch.

If you have already built the *Li'l Pulser Mk2 Train Controller* into the smaller specified case, you will need another box to house these components. Either way, once you've mounted all those components in the box, it's just a matter of connecting it up as per the wiring diagram shown in Fig.7.

Parts List – Automatic Train Controller with Whistle Sounds

1 assembled Li'l Pulser Model Train Controller, Mk2 (July14)
1 assembled Steam Train Whistle module (March20)
1 assembled Level Crossing (July22)
1 assembled Semaphore Signal (March23)
1 assembled Chuff Sound module (see below)
1 ISD1820-based sound recording and playback module (MOD1) **[eg, Jaycar XC4605, SC5081 – or eBay]**
1 single-sided or double-sided PCB coded 09109221, 50 × 51mm available from the PE PCB Service
1 5V DC 500mA supply
3 5kΩ mini single-turn top-adjust trimpots (VR1-VR3)
1 16-pin DIL IC socket (for RLY1)
1 14-pin DIL IC socket (for IC1)
1 DPDT toggle switch (S1) **[Jaycar ST0355]**
1 SPST momentary pushbutton (S2) **[Jaycar SP0711]**
1 76mm 8Ω loudspeaker (SPK1) **[Jaycar AS3006]**
1 TE Connectivity V23105A5001A201 5V DC coil DPDT 3A relay or equivalent (RLY1) **[element14 1652604, Digi-Key PB383-ND]**
1 Comus RI80SMDM-0510-G1 miniature SPST reed switch **[Digi-Key 1835-1161-1-ND]**
1 small rare earth magnet **[Jaycar LM1622]**
11 1mm PCB pins
various lengths of light-duty hookup wire

Semiconductors
1 PIC16F1455-I/P microcontroller programmed with 0910922A.HEX, DIP-14 (IC1)
1 BC547 45V 100mA NPN transistor, TO-92 (Q1)
1 5mm red LED (LED1)
1 5mm blue LED (LED2)
1 5mm white LED (LED3)
1 5mm yellow LED (LED4)
1 1N4004 400V 1A diode (D1)
6 1N4148 75V 200mA signal diodes (D2-D7)

Capacitors
1 100µF 16V radial electrolytic
8 100nF 50V radial multi-layer ceramic or MKT

Resistors *(all ¼W 1% axial)*
2 10kΩ
1 4.7kΩ
1 1.5kΩ
4 1kΩ
3 680W

Chuff Sound module

1 single-sided or double-sided PCB coded 09109222, 59 × 30mm available from the PE PCB Service
1 5V DC regulated plugpack or other 5V floating supply **(cannot be shared with the Train Controller module)**
2 8-pin DIL IC sockets (**optional**; for IC2 and IC3)
1 10kΩ mini single-turn top-adjust trimpot (VR4)
1 1kΩ mini single-turn top-adjust trimpot (VR5)
1 SPDT toggle switch (S3) **[Jaycar ST0335]**
1 57mm 8Ω 250mW loudspeaker (SPK2) **[Jaycar AS3000]**
6 1mm PCB pins
various lengths of light-duty hookup wire

Semiconductors
1 PIC12F675-I/P 8-bit microcontroller programmed with 0910922C.HEX, DIP-8 (IC2)
1 LM386N-1 audio amplifier, DIP-8 (IC3) **[Jaycar ZL3386]**
1 LM4040 5V shunt regulator or 1N4732 4.7V zener diode (ZD1)
4 1N4148 75V 200mA signal diodes (D8-D11)

Capacitors
2 100µF 16V radial electrolytic
1 10µF 16V radial electrolytic
1 100nF 50V radial multi-layer ceramic
1 47nF 63V MKT
1 22nF 63V MKT

Resistors *(all ¼W 1% axial)*
1 15kΩ
1 10kΩ
1 8.2kΩ
1 10Ω

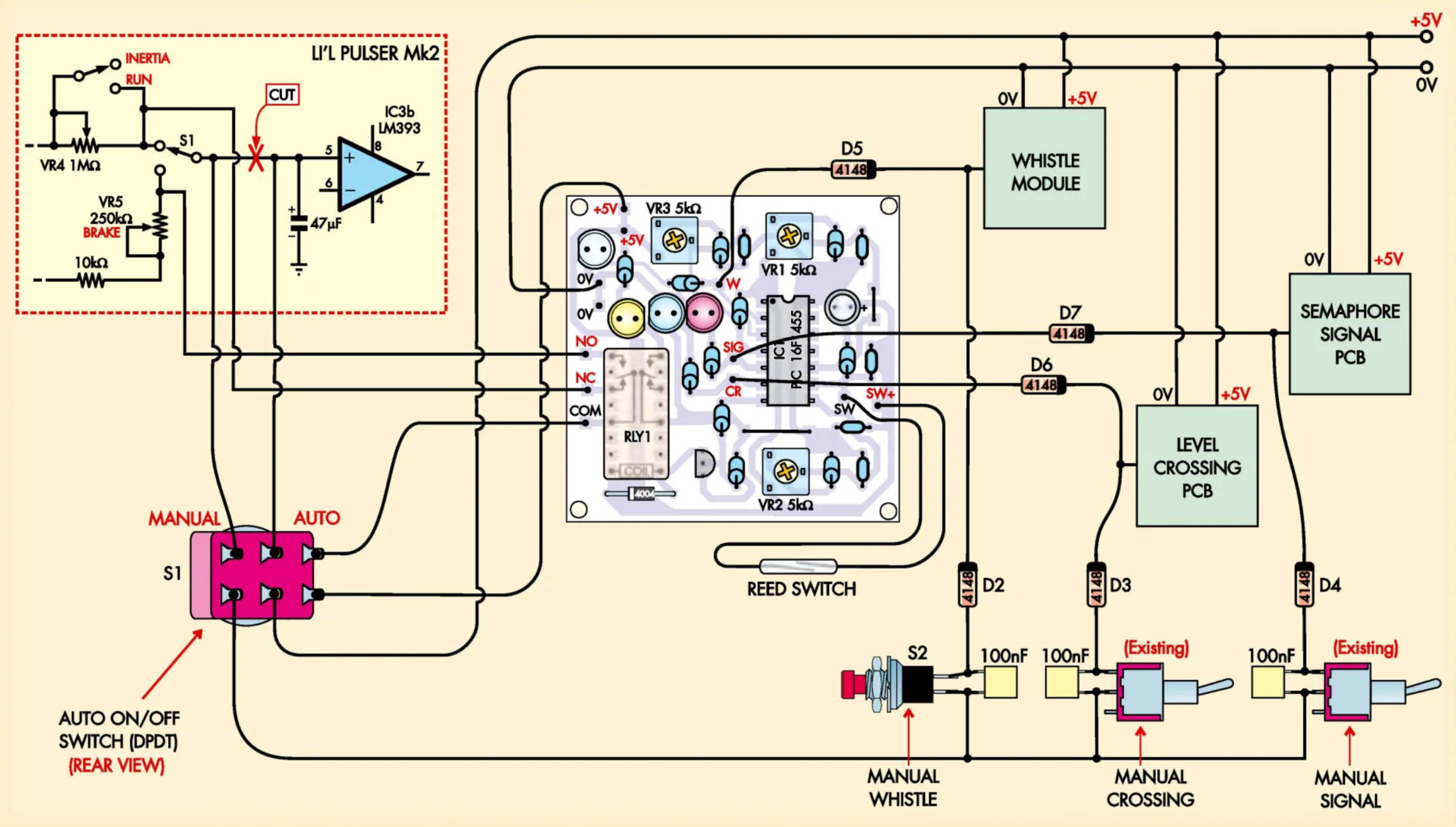

+5V
0V
LI'L PULSER Mk2
INERTIA
RUN
CUT
IC3b
LM393
S1
VR4 1MΩ
VR5
250kΩ
BRAKE
10kΩ
47µF
5
6
7
8
4
WHISTLE MODULE
D5
4148
+5V
0V
VR3 5kΩ
VR1 5kΩ
W
NO
NC
COM
SIG
CR
SW+
SW
IC1 PIC 16F1455
RLY1
COIL
4004
VR2 5kΩ
D7
4148
D6
4148
SEMAPHORE SIGNAL PCB
LEVEL CROSSING PCB
MANUAL
AUTO
S1
REED SWITCH
D2
D3
D4
S2
100nF
100nF
(Existing)
100nF
(Existing)
AUTO ON/OFF SWITCH (DPDT)
(REAR VIEW)
MANUAL WHISTLE
MANUAL CROSSING
MANUAL SIGNAL

Fig.7: once you've built all the modules, wire them up as shown here. The manual switches can still be used to control the Semaphore and Level Crossing if S1 is in the manual position. The Chuff Module wiring is shown separately, in Fig.6. Note that you will need to cut a track on the Li'l Pulser Mk2 PCB before adding the four wires that go to S1 and the Control Module.

The only tricky part is interfacing with the *Li'l Pulser Mk2 Train Controller*. To do this, you must cut the connection between the middle contact of switch S1 and the 47µF capacitor and attach flying leads to the brake side of S1, the run side of S1, the central contact of S1 and the positive terminal of the 47µF capacitor – see Fig.7.

Getting it all going

Before applying power to the finished system, check the wiring to the modules. Attach the small magnet to the front of the locomotive, ideally on the underside near the front. Also check that the train rails and wheels are clean before proceeding.

Switch the Auto on/off switch to off (manual). Increase the train's speed to that previously used to determine where to place the reed switch.

Now change the switch back to on (ie, automatic control) and adjust potentiometer VR1 on the *Automatic Controller* PCB so that the *Signal* goes green close to one second after the train has stopped.

Next, adjust VR3 to what you think the driver's reaction time should be to start the train once the *Signal* goes green. I set this to one second. Once the *Semaphore* goes off, the train should start to move away and the *Level Crossing* should close, flashing its LEDs and playing bell sounds. The whistle should sound four seconds after the train starts moving again.

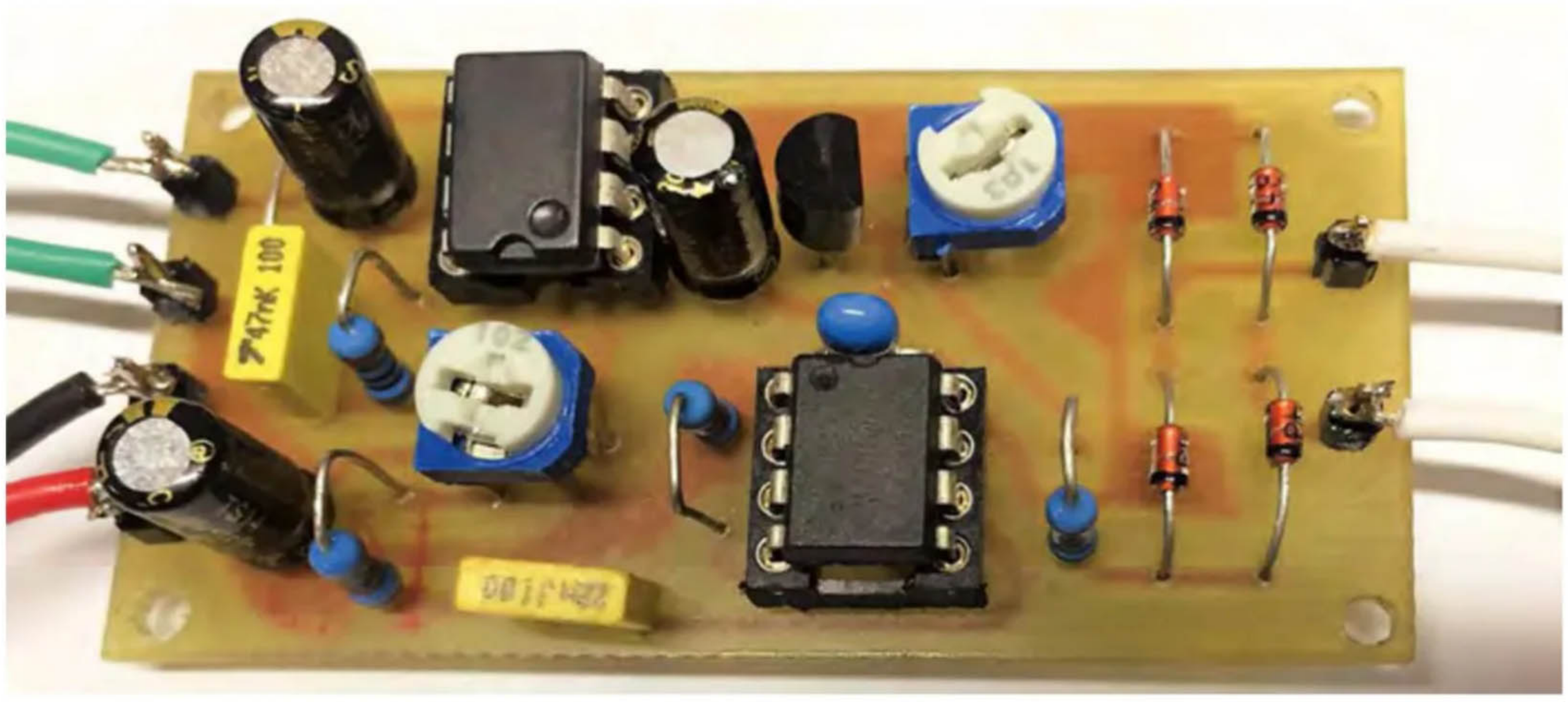
Finally, adjust VR2 so that the *Crossing* opens once the train has passed through. Note that if this time is set too long, the train could pass the reed switch again before the *Crossing* closes. The result is that the train won't stop when it passes over the reed switch.

Chuff Module wiring

Connect the track input wires on the *Chuff* module to the railway tracks and wire in the on/off switch and power supply, as shown in Fig.6. Switch it on and adjust the speed controller so that the train is travelling at a maximum realistic speed (not necessarily the speed it runs with the controller supplying full voltage).

Using a digital voltmeter, measure the voltage between the GP2 input (pin 5) of IC1 and ground, and adjust VR4 until the voltage reads 3.3V. Wind back the speed and the chuff rate should decrease until the train is stopped, at which point the sound will revert to panting. The sound level can be adjusted using potentiometer VR5.

As mentioned earlier, if you can't achieve 3.3V at pin 5 of IC1 by adjusting VR4, you'll have to replace the 15kΩ resistor with a higher or lower value. You shouldn't have to increase the value, but you might have to reduce it if you don't get 3.3V at pin 5 of IC1 even with VR4 at its maximum.



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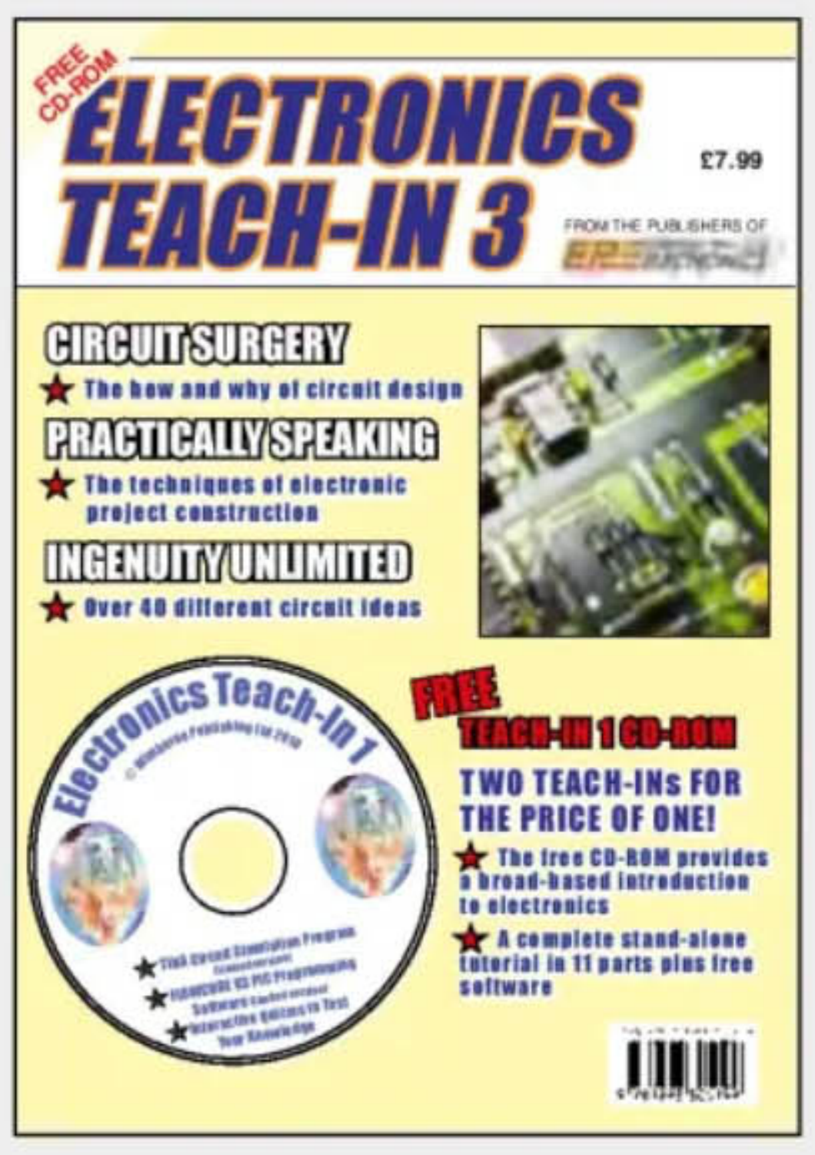

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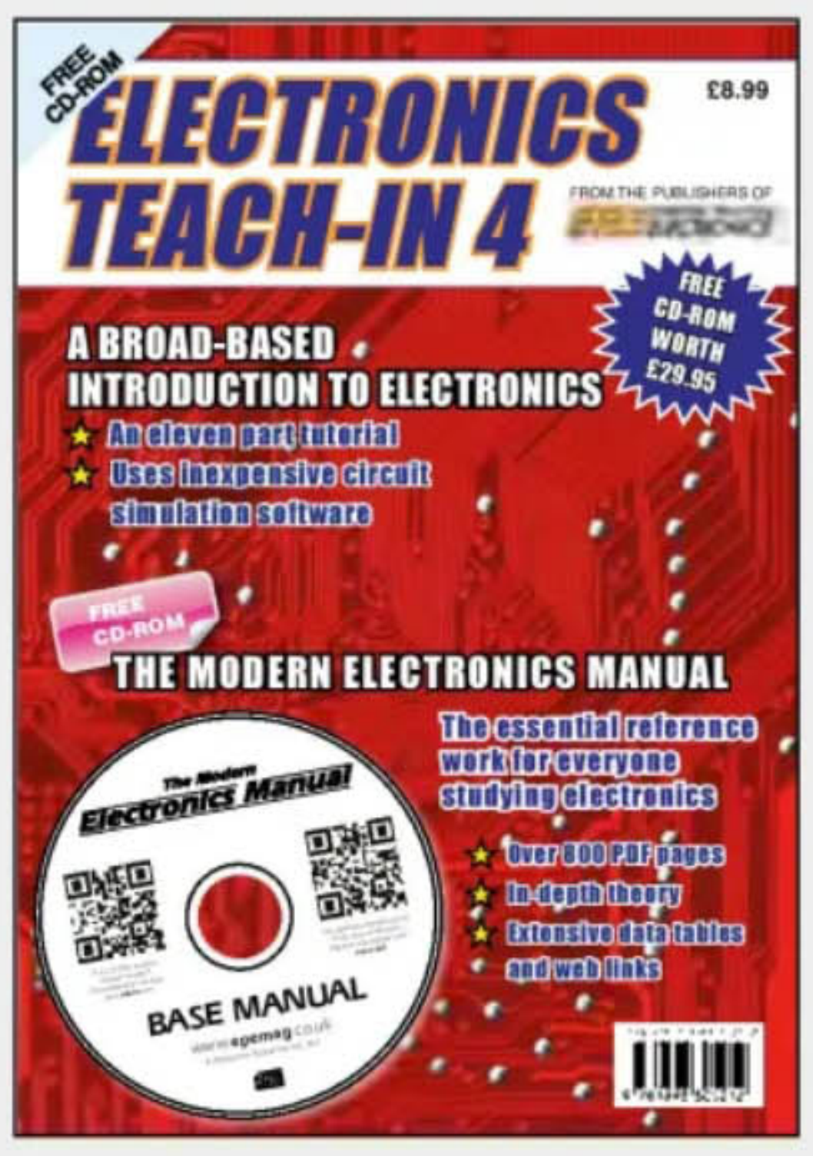
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MULTI-STAGE BUCK-BOOST BATTERY CHARGER

By Tim Blythman

This simple, low-cost add-on turns our *Buck-Boost Driver* into a fully featured multi-stage battery charger. It can be used with multiple battery chemistries but is especially useful for lead-acid types. Its features include adjustable absorption and float charge voltages, temperature compensation, a long-term 'storage' mode, charge status display and low quiescent current.

When we presented the *Buck-Boost LED Driver* project (*PE*, June 2023), we explained that you could also use it to charge batteries from a wide range of DC input voltages.

However, in its original form, it only acted as a single-stage battery charger. For proper charging, especially with lead-acid batteries, you want a multi-stage charger and that's what this simple add-on provides.

One beneficial side-effect of its wide input voltage range is that you can use low-cost, high-power laptop chargers (typically delivering around 19V) as the power source.

The Charger Adaptor

We call this add-on board the *Charger Adaptor* (*Adaptor* for short). Combined with the *Buck/Boost Driver*, we have a complete battery charging system. With the *Adaptor*, it can now perform bulk, absorption, float and storage charging. It does this while retaining the original *Driver's* wide input voltage range, high efficiency and high current delivery.

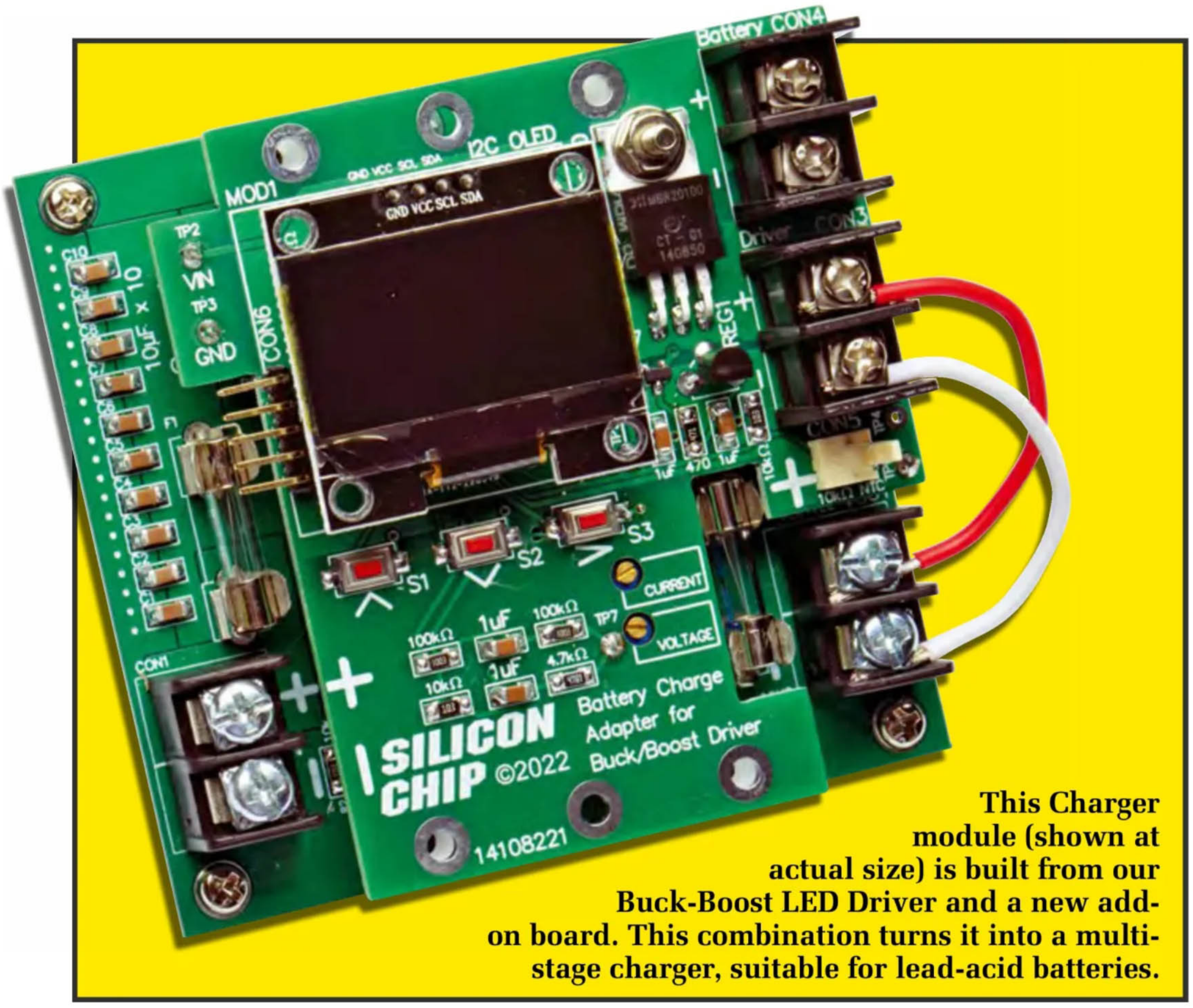
The *Adaptor* has a compact OLED screen to report the *Charger's* current activity and monitor the battery and power supply status. Along with this screen, three buttons allow the *Charger* to be configured.

The *Charger* has been conceived mainly for use with 12V and 24V lead-acid type batteries and their various equivalents and substitutes, such as AGM and even lithium types. But, with so many of the *Driver* and *Adaptor* parameters being adjustable, it could also be used with other battery types. That's especially true of the $LiFePO_4$ batteries that are designed to mimic lead-acid types.

You can use the original *Driver* design if all you need is a float charger. You would simply set its output voltage to the float voltage for the battery. For many 12V batteries, such as lead-acid types, this is typically around 13.5-13.8V. The current limit can then be set at an appropriate level for the particular arrangement of battery, supply and wiring used.

The *Driver's* current limiting means that even if a deeply discharged battery is connected, it can be safely charged up to its float level without damaging the battery, overloading the supply or damaging the wiring. But float charging alone will not make the best use of a battery's capacity, nor is it the quickest way to charge.

Bulk charging applies a higher current (and higher voltage) to the battery to quickly raise the battery's charge to near 80% of its capacity. Absorption charging follows. This involves applying a voltage above the float voltage to bring the battery up to around 95% of its capacity. After these stages, it will revert to float charging to maintain the charge level near its maximum.



This Charger module (shown at actual size) is built from our Buck-Boost LED Driver and a new add-on board. This combination turns it into a multi-stage charger, suitable for lead-acid batteries.

To enable bulk and absorption charging, we need to be able to increase the *Driver's* output voltage. We should also monitor the battery current and voltage to know the battery condition.

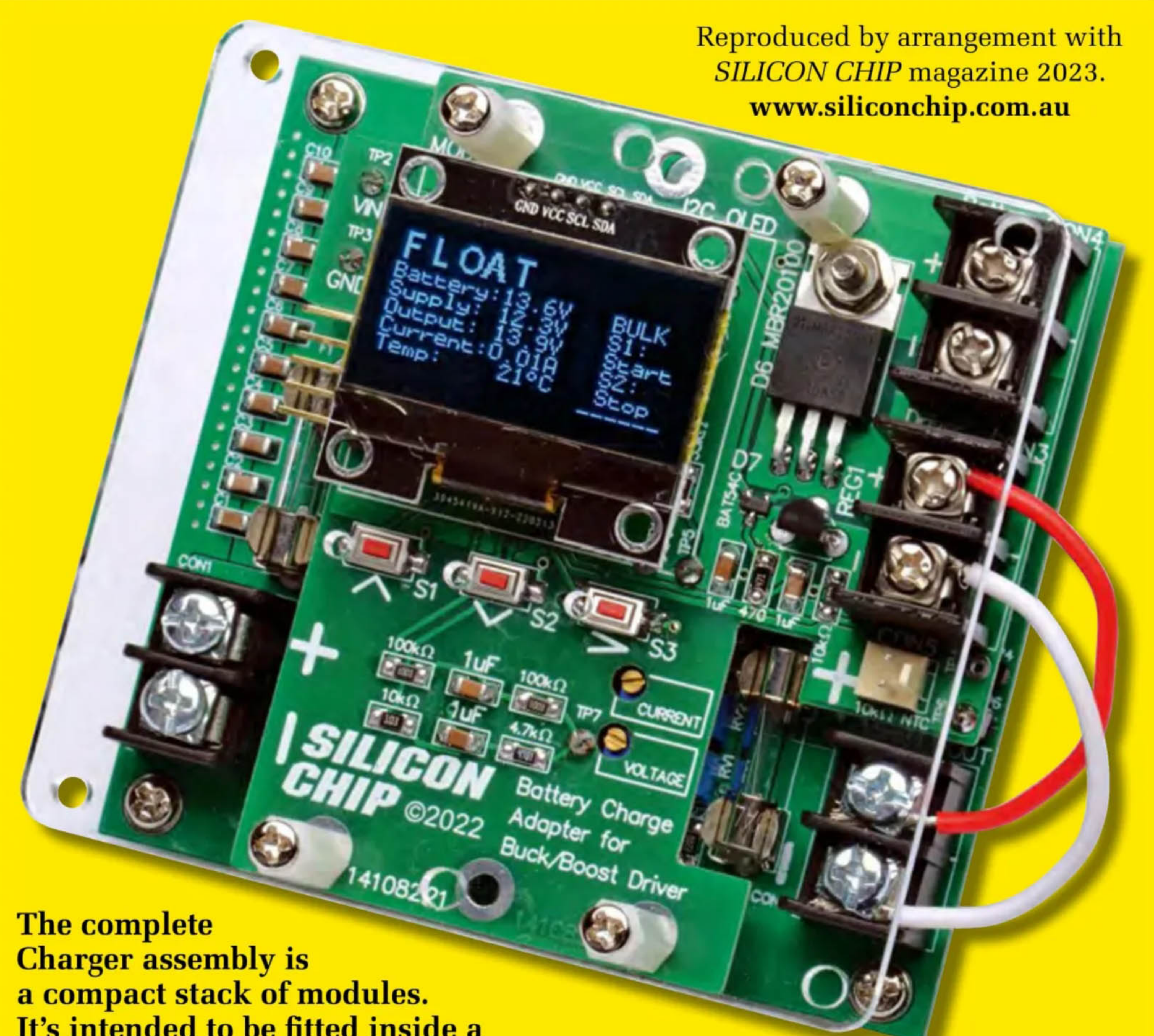
Ideally, a battery charger can monitor the battery temperature and adjust its output voltage to provide the optimum voltage levels for a given temperature. Cell voltages vary with temperature, so if you use a fixed charging voltage under varying ambient conditions, you can end up under-charging or over-charging the battery.

The *Charger* solves this by monitoring the battery temperature with an NTC thermistor and calculating the appropriate charge voltage based on a user-specified temperature coefficient.

The *Charger* is highly configurable. The default settings are functional, if not optimal, for 12V lead-acid-type batteries, providing the current-limit setting is appropriate.

Note, though, that it is possible to program settings that may cause damage if you aren't familiar with how multi-stage battery chargers work. And because the current limit on the *Driver* cannot be set any lower than around 1.8A, it is not practical to use with small batteries that cannot handle this rate of charge.

Sealed lead-acid types of around 7Ah (such as the type commonly sold as NBN backup batteries) are about the smallest we suggest charging with this device. These typically specify a maximum charge current of around 2A. The default bulk charge values (such as time and start voltage) also assume a battery no smaller than that.



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The complete Charger assembly is a compact stack of modules. It's intended to be fitted inside a cabinet, but the front acrylic cover panel could also be used as a mounting bezel to allow the display to be seen from outside, or it can be used as a standalone assembly.

Features and Specifications

- ***Input:*** **11.3V to 35V DC at up to 10A**
- ***Output:*** **from 7V to 34V DC**
- ***Charge current:*** **up to 8A (extra heatsinking may be needed over 5A)**
- **Suitable for most 12V and 24V batteries**
- **Can perform bulk, absorption, float and storage charging**
- **Charging currents, voltages and times can be adjusted**
- **Compact OLED display for configuration and complete battery status**
- **Onboard pushbuttons for configuration and setting**
- **Battery voltage temperature compensation**
- **10mA typical quiescent current, down to 1mA with power supply off**

Charger Adaptor details

The *Charger Adaptor* connects to the *Buck/Boost LED Driver* at four of its existing test points. While we didn't originally envision this use, they're the perfect place to interface another circuit. Fig.1 shows the circuit of the *Adaptor* and how it connects to the *Driver*. The *Adaptor* is based around IC3, a PIC16F1459 microcontroller.

We've numbered the various components across the two boards as though they are one circuit, so there should be no confusion about which part is being discussed.

Output terminal CON2 on the *Driver* board connects (by high-current wiring) to CON3 on the *Adaptor*, with the battery connected to the *Adaptor's* CON4.

This is so we can insert high-current schottky diode D6 in the charging path to prevent the battery from discharging into the *Driver* when the power supply is off. It also allows us to monitor the charger output voltage and battery voltage independently.

The *Driver's* CON1 input terminals are used as the incoming supply connection, just as in any other type of *Driver* application.

The four test points we connect to on the *Buck/Boost* board (TP2, TP3, TP5 and TP7) are numbered identically on both boards and connect directly through low-current pin headers.

The input supply of the *Buck/Boost* board is available at TP2, and this feeds into a 100kΩ/10kΩ divider to ground, allowing the analogue-to-digital (ADC) peripheral of IC3 (via analogue input AN6, pin 14) to monitor the input voltage. A similar divider monitors the output voltage at CON3 connected to the *Driver* output, while a 1MΩ/100kΩ divider is used to sense the battery voltage at CON4.

The relatively high value of those two resistors reduces the current drawn from the battery while charging power is unavailable.

A 10kΩ NTC (negative temperature coefficient) thermistor is connected across CON5, forming the top half of a voltage divider with a 10kΩ fixed resistor. The thermistor is placed in contact with the battery under charge to allow its temperature to be monitored.

TP5 is connected to a similar 33kΩ/10kΩ divider so the micro can monitor the charging current. All five dividers include 100nF capacitors across their lower resistors to reduce noise and provide a low input impedance to the ADC. They connect to pins 7, 9, 12, 13 and 14 of IC3.

With a 3.3V rail and reference, and 10:1 dividers, IC3 can measure voltages up to 36.3V with a resolution of around 0.03V. Current measurement is limited by the voltage output by the *Driver* and can thus be measured up to the full capacity of the *Driver*.

The remaining connection from the *Adaptor* to the *Driver* is at TP7, which

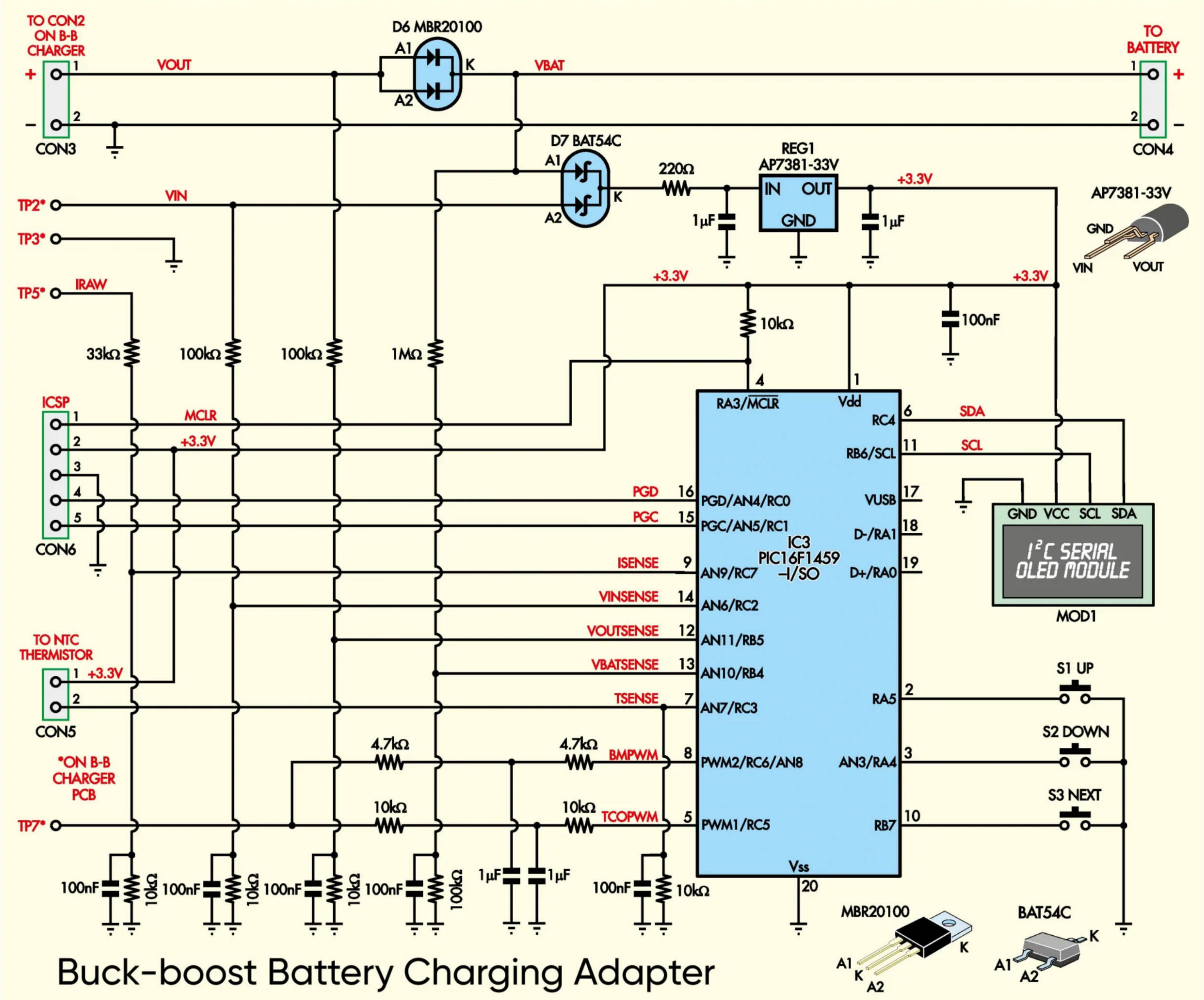

TO CON2 ON B-B CHARGER
CON3
VOUT
D6 MBR20100
A1
A2
K
VBAT
TO BATTERY
CON4
D7 BAT54C
220Ω
REG1 AP7381-33V
IN
OUT
GND
1µF
+3.3V
AP7381-33V
GND
VIN
VOUT
TP2*
TP3*
TP5*
VIN
IRAW
33kΩ
100kΩ
100kΩ
1MΩ
10kΩ
100nF
ICSP
MCLR
+3.3V
CON6
RA3/MCLR
Vdd
RC4
RB6/SCL
SDA
SCL
PGD
PGC
PGD/AN4/RC0
PGC/AN5/RC1
VUSB
D-/RA1
D+/RA0
IC3 PIC16F1459 –I/SO
ISENSE
AN9/RC7
VINSENSE
AN6/RC2
VOUTSENSE
AN11/RB5
VBATSENSE
AN10/RB4
TSENSE
AN7/RC3
GND VCC SCL SDA
I²C SERIAL OLED MODULE
MOD1
TO NTC THERMISTOR
CON5
*ON B-B CHARGER PCB
TP7*
4.7kΩ
BMPWM
PWM2/RC6/AN8
10kΩ
TCOPWM
PWM1/RC5
RA5
AN3/RA4
RB7
S1 UP
S2 DOWN
S3 NEXT
Vss
MBR20100
BAT54C
Buck-boost Battery Charging Adapter

Fig.1: there isn't much to the Adaptor circuit as it is mostly just components to connect the added microcontroller, IC3, to various points on the Driver board for monitoring and control. The microcontroller modifies the Driver's output voltage by biasing its feedback pin via TP7.

is connected to the feedback comparator inside IC1 on the *Driver* PCB and usually sits at 1.23V. If this rises, the *Driver* will decrease the output voltage. Conversely, a voltage reduction will cause the output voltage to rise. So we can modify the set output voltage by sourcing or sinking current via TP7.

The pair of RCR networks attached to TP7 do just that. PWM (pulse-width modulated) waveforms from pins 5 and 8 of IC3 are smoothed by the first resistor of each pair and its associated 1µF capacitor.

The second resistor in each network turns that smoothed voltage into a small control current which can raise or lower the *Driver's* output voltage. The smoothing is necessary as any ripple will be translated into a corresponding ripple at the *Driver's* output.

The two RCR networks are used for different purposes. The network with the two 10kΩ resistors is used to apply the minor temperature compensation adjustments. The network with the two 4.7kΩ resistors can sink or source more current and thus make a larger adjustment. This is used to set the bulk and absorption voltages.

With a 3.3V supply, a 37% duty cycle will result in around 1.23V and not cause any change in the *Driver* output. A fixed low signal or 0% duty cycle (which gives 0V at the input to the RCR network) will cause the *Driver* output voltage to rise about 15%.

Note that the change is proportional to the output voltage because the fixed 1.23V comes from the variable divider on the *Driver* board (including VR1).

While we could have used one RCR network and PWM peripheral, the firmware is slightly simplified by keeping them separate.

So microcontroller IC3 on the *Adaptor* board can monitor the various voltages on the *Driver* and adjust its output voltage to provide several different charge modes.

One of the interesting quirks of the *Driver* design is that the actual current and voltage setpoints (as set by the trimpots on the *Driver*) are not known to the *Adaptor* board. This means that some parameters are set as proportions of other values.

Monochrome I^{2}C OLED module MOD1 is connected to pins 6 and 11 of IC3 as well as the 3.3V supply rail and ground. IC3 uses a bit-banged I^{2}C interface to control MOD1.

Tactile pushbuttons S1, S2 and S3 connect between ground and pins 2, 3 and 10 of IC3. The OLED, MOD1 and these three buttons provide the user interface for the *Adaptor*.

Adaptor power supply

Power for the *Adaptor* is primarily taken from TP2 and TP3, which are connected to CON1 input via fuse F1 on the *Driver*. The *Adaptor's* supply current flows through common-cathode dual diode D7 and a 220Ω resistor to REG1, a 3.3V regulator which provides power to the PIC16F1459 microcontroller (IC3), which provides all the multi-stage charging functions.

REG1 has been chosen for its wide input range and low quiescent current. The 220Ω resistor gives the regulator more headroom to operate at high input voltages by sharing some dissipation with REG1.

A pair of 1µF ceramic capacitors provide input and output bypassing for REG1. D7 is fed at its second anode from the battery positive at CON4, so the *Adaptor* is still powered even if its primary power supply is absent. Thus, IC3 can remember the charging state even when the incoming supply is off.

Microcontroller IC3 has a 100nF bypass capacitor between its 3.3V supply (pin 1) and ground (pin 20), while pin 4 ($\overline{\text{MCLR}}$) is pulled up by a 10kΩ resistor to the 3.3V rail to prevent spurious resets.

The usual in-circuit programming pins (1, 4, 15, 16 and 20) are brought out to optional ICSP programming header CON6, so IC3 can be programmed in-circuit if necessary.

Powering the Charger

For a couple of reasons, we recommend that the input voltage to the *Charger* via CON1 is higher than the typical battery voltage if possible.

The first reason is that the *Driver* is more efficient when reducing the voltage in its 'buck' or step-down mode.

The second is that the *Adaptor* PCB will draw power from whichever anode of D7 is at a higher voltage. If the output fuse F2 on the *Driver* blows and the supply is lower than the battery, the battery will slowly drain.

Neither of these are critical, but we thought they would be worth mentioning so you can get the most out of the *Charger*.

Firmware control

The operation of the *Adaptor* and thus the *Charger* is controlled by microcontroller IC3.

The default mode is equivalent to the float mode that is available with an unmodified *Driver*, as no adjustment is made to the output voltage. The three voltages (input, outage and battery), the output current and thermistor temperature are displayed on the screen.

It's assumed that the *Driver* output current is flowing out of CON2, into CON3 and then to the battery at CON4. Up to 10mA is actually used to power the *Adaptor*, but that is a small enough amount to be ignored.

If you have anything else that can draw current from CON2 (or further downstream), you will have to take that into account, especially when setting the bulk charge current cutoff. Excess current drain may prevent the bulk stage from ending correctly.

When the *Adaptor* detects that the supply is absent, it goes into a lower-power mode and blanks the OLED, reducing the current draw to around 1mA. This is necessary because the *Adaptor* will be running from the battery at these times.

The supply could be absent for many reasons, depending on how the *Charger* is powered, and it is expected to be a relatively regular occurrence.

The *Adaptor* may also display 'PWR FAULT', meaning that the supply has been detected, but there is no output from the *Driver*. This would typically indicate a problem with the *Driver*, such as a blown fuse. This situation requires attention, as the *Charger* will not be able to charge a battery until the *Driver* can provide an output.

The temperature at the NTC thermistor is monitored by measuring the voltage at its divider junction and mapping that to temperature via a table. If the thermistor has an open-circuit or short-circuit fault, that is detected and displayed.

If there is no fault, then the temperature compensation is applied in proportion to a coefficient set by the user. This is one of the parameters that is set as a proportion, and we'll discuss the particulars of this during setup and testing.

Multi-stage charging

A typical multi-stage charger will have bulk, absorption and float modes. In bulk mode, current is supplied to the battery up to a set current limit and up to a set voltage (higher than the float voltage). When this voltage is reached and the current begins to fall off, such a charger will switch to a voltage-limited absorption mode.

The current tapers off until the *Charger* considers that the absorption mode is complete, after which the lower fixed float voltage is applied.

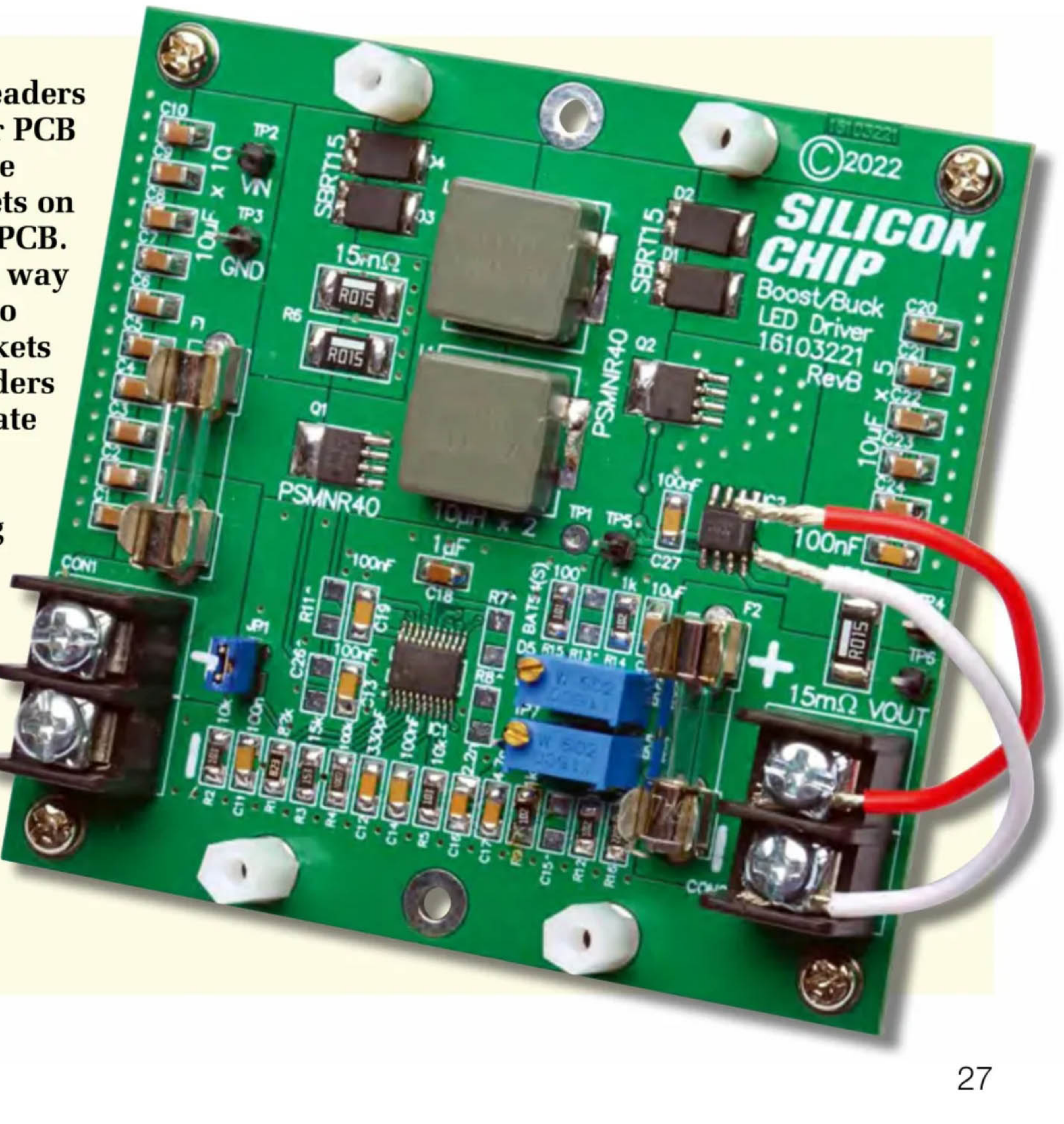
The *Charger* works much like this, although the distinction between bulk and absorption is not that important. We call this the combined bulk/absorption stage or just 'bulk' for brevity. The *Driver* is set to supply the float voltage by default, but during the bulk/absorption stage, the *Adaptor* increases the output voltage by sinking a small current from TP7.

The bulk/absorption stage is started when the battery voltage falls below a given setpoint. This setpoint is chosen with the assumption that, at this voltage, the battery is pretty flat and can therefore take a substantial charge. You can also trigger the bulk/absorption stage manually.

When the *Driver's* current limiting dominates, this is the bulk phase. After a while, as the battery voltage rises, the current will begin to taper off, equivalent to the absorption stage.

The *Adaptor* has a current setpoint, below which it assumes that the bulk and absorption stages have completed. Then, the float settings are reinstated and the output voltage drops. A timer also limits the maximum time in bulk/absorption stages (recommended by many battery manufacturers).

There is also a 'storage' stage, intended for batteries that are left



Single pin headers on the Driver PCB connect to the header sockets on the Adaptor PCB. The simplest way to do this is to slide the sockets onto the headers and then locate the Adaptor PCB using the mounting hardware.

continuously on float charge. In storage mode, the *Adaptor* reduces the *Driver's* output voltage below the float voltage. Periodically (once a week), it will start a bulk charge to 'equalise' the battery. That's assuming there isn't a load on the battery, which will trigger the *Charger* before then.

This is the best strategy for getting a long life from a 'standby' lead-acid battery. Remember that keeping a battery under float charge for extended periods can damage it.

This state's commencement and ending are simply controlled by timers and can also be disabled by setting the starting timer to zero. Although not as critical as bulk/absorption charging, the amount by which the voltage is decreased in storage mode is adjustable.

The OLED and buttons allow various parameters to be set and configured. As you can see from the photos, holes in the *Adaptor* PCB give access to the current and voltage trimpots on the *Driver* PCB so that all settings can be changed in the assembled state.

We'll delve deeper into the configuration options after the assembly steps. The default software settings are pretty conservative and should be functional (if not optimal) for most common lead-acid battery types. They depend on appropriate *Driver* settings to work correctly.

Construction

The *Adaptor* is fairly self-contained, but won't do anything useful without the *Driver*, so we'll start by assuming that you have a *Driver* PCB assembled as described in the June 2023 issue. If you haven't assembled the *Driver* yet, we don't have any changes to the original build instructions. However, you could substitute soldered wires for the barrier terminals between CON2 on the *Driver* and CON3 on the *Adaptor*.

The *Adaptor* is built on a 75mm × 80mm double-sided PCB coded 14108221, which is available from the *PE PCB Service*. The component locations are shown in Fig.2.

Like the *Driver*, the *Adaptor* uses many surface-mounting components, so you will need flux paste, tweezers, solder-wicking braid, a fine-tipped iron, a magnifier and preferably a solder fume extractor.

Fortunately, the parts are not as tightly packed as on the *Driver*, so the PCB assembly is straightforward.

Start by soldering IC3, the PIC16F1459 microcontroller. Apply flux to the pads and rest the part on the pads, being sure to align the pin 1 markings. Tack one pin in place and check that the pins remain aligned before soldering the rest of the pins. Use solder wick to remove any bridges and apply extra flux if needed.

The SOT-23 diode (D7) is the other part with small pins, although once the pins are aligned, it's easy to solder. Be sure to align the part with the PCB silkscreen and, like the IC, tack one lead and confirm the part is flat and square before soldering the remaining pins.

Fit the M3216/1206-size ceramic capacitors next, working through each value in turn. There are two different values that you must not mix up.

Follow with the various resistors. There are a few different values; they are marked with codes that indicate their values. Tactile switches S1-S3 are soldered similarly to the other surface-mounting parts.

Now clean the PCB of any excess flux using an appropriate solvent. Allow the PCB to dry thoroughly before proceeding. The remaining parts are through-hole types and won't require extra flux.

REG1 is the TO-92 package regulator. Ensure its body lines up with the PCB silkscreen before soldering it.

D6 is a TO-220 power diode that is mounted flat against the PCB. Bend the leads around 7mm from the body and slot them into the holes in the PCB. Secure the tab using the 8mm screw, nut and shakeproof washer, being sure not to twist the leads. When you are happy with the location of the diode, solder its leads and trim them.

This arrangement is suitable for a few watts of dissipation. If you plan to run the *Charger* above 5A, you might need to enhance the heatsinking. This could be as simple as clamping a steel or aluminium strip with a 3mm hole drilled in it between the diode and PCB. Take care that it can't short against any other components.

The four-way header for MOD1 is a female type to match the male header on the OLED. When soldering this, check that it is perpendicular to the PCB to allow the OLED to mount neatly.

CON3 and CON4 can be fitted next. As noted, you could omit CON3 on the *Adaptor* PCB and CON2 on the *Driver* PCB and run heavy-duty wires directly. However, we recommend that you keep the barrier terminals to retain modularity.

These two parts may require extra heat from the iron since they are physically larger and also sit on substantial copper areas of the PCB, so turn up the iron if possible while soldering them.

CON5 is a two-way header for the thermistor. We've used a simple

Parts List – Buck/Boost Charger Adaptor

1 assembled Buck-Boost LED Driver Module **[*PE*, June 2023]**
1 double-sided PCB coded 14108221 measuring 75mm x 80mm available from the *PE PCB Service*
2 2-way barrier terminals, 8.25mm pitch (CON3, CON4)
1 lug-mount 10kΩ NTC thermistor on cable with two-pin 2.54mm XH plug
1 2-way JST XH 2.54mm header (CON5)
1 5-way right-angle male header (CON6; optional, for ICSP)
1 1.3-inch OLED with 4-pin I^{2}C interface (MOD1)
1 4-way header socket (for MOD1)
4 single pin header sockets (TP2, TP3, TP5, TP7)
4 single header pins (TP2, TP3, TP5, TP7)
2 2-pin 6×3mm SMD tactile switches with black actuators (S1, S2)
1 2-pin 6×3mm SMD tactile switch with red actuator (S3)
4 5-6mm panhead M3 machine screws
4 15-16mm panhead M3 machine screws
4 10mm-long M3-tapped Nylon spacers
4 15mm-long M3-tapped Nylon spacers
1 75 × 80mm laser-cut clear acrylic cover plate **[Cat SC6567]**
1 8mm-long panhead M3 machine screw (for D6)
1 M3 shakeproof washer (for D6)
1 M3 hex nut (for D6)
2 5cm lengths of 10A wire (for CON2-CON3)

Semiconductors
1 PIC16F1459-I/SO micro programmed with 1410822A.HEX, SOIC-20 (IC3)
1 AP7381-33V-A 3.3V linear regulator, TO-92 (REG1)
1 MBR20100CT 20A 100V dual schottky diode, TO220 (D6)
1 BAT54C dual common-cathode SMD schottky diode, SOT-23 (D7)

Capacitors *(all SMD M3216/1206-size multi-layer ceramic)*
4 1µF 50V X7R
6 100nF 50V X7R

Resistors *(all SMD M3216/1206-size ⅛W 1%)*
1 1MΩ 3 100kΩ 1 33kΩ 7 10kΩ 2 4.7kΩ 1 220Ω

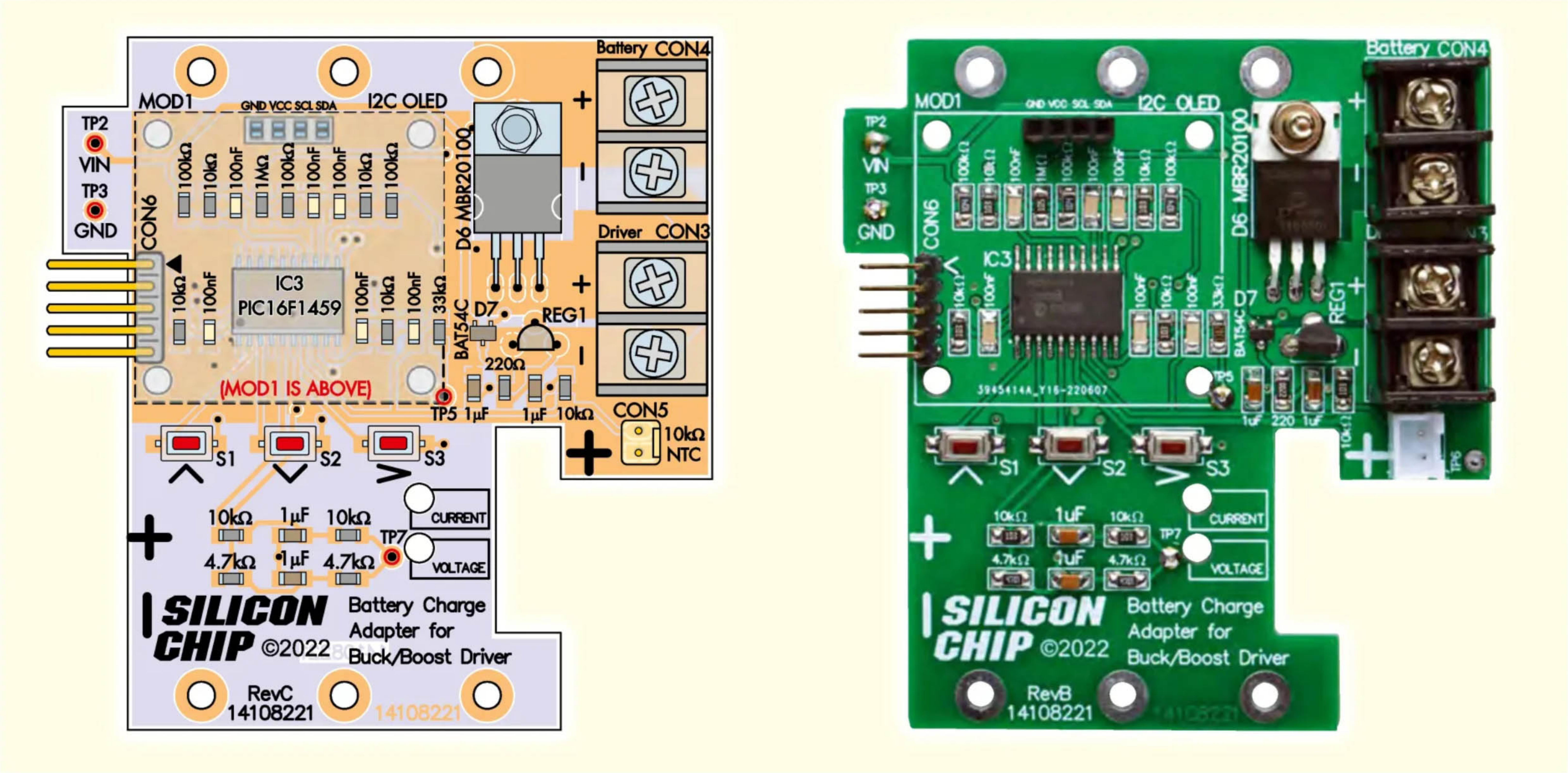


Fig.2: the Adaptor has a mix of surface-mounting and through-hole parts and should be straightforward to assemble. If you take care to orient IC3 correctly and don't mix up the (unmarked) capacitors, you should have no trouble. The four test points are fitted with sockets on the underside to connect to pin headers on the Driver; see the photos for details.

polarised header on our prototype, but would prefer JST-type headers to match pre-wired thermistor leads if those are used. They are 2.54mm pitch headers, so they will fit the same pads. The thermistor is not polarised, so the orientation is not important.

Finally, to program your microcontroller you need to fit a right-angled ICSP header at CON6.

Programming

You can use a PICkit 3, PICkit 4 or Snap programmer to program the PIC16F1459. You should set the PICkit to provide a 3.3V supply because this is what the circuit has been designed to use.

Otherwise, apply 10-35V between TP2 (positive) and TP3 (negative) to power the micro via the regulator. Connect your programmer as indicated by the arrow marks and upload the 1410822A.HEX file using the MPLAB X IPE.

Note that the grounds at CON3 and CON4 are not connected to the circuit ground at TP3 and the ICSP header, so you can't use them for a programming ground connection. This arrangement prevents unexpected currents from flowing through the *Adaptor's* digital ground circuit.

Now disconnect power before the next step.

Testing

Next, connect the thermistor and plug the OLED module into the header, then apply 10-35V DC via TP2 (positive) and TP3 (negative). The OLED screen should start up after a second or two, displaying a roughly correct supply voltage.

The temperature reading should be sensible. If T_ERR is displayed, there may be a circuit problem, or an incorrect thermistor has been used.

If the displayed supply voltage is way off (say, by more than 10%), you may have mixed component values in the dividers.

Now is the time to fix any problems, before the *Adaptor* is let loose and connected to the *Driver*.

Mechanical assembly

It's best to temporarily detach the OLED while assembling the boards. They can be quite fragile as they are made of thin glass.

To help align all the parts, start by fitting four 10mm spacers to the underside of the *Driver* in the extreme corners and attach them using short M3 screws. These will act as feet. Remove any other spacers under the *Driver* to allow the *Adaptor* to be fitted above.

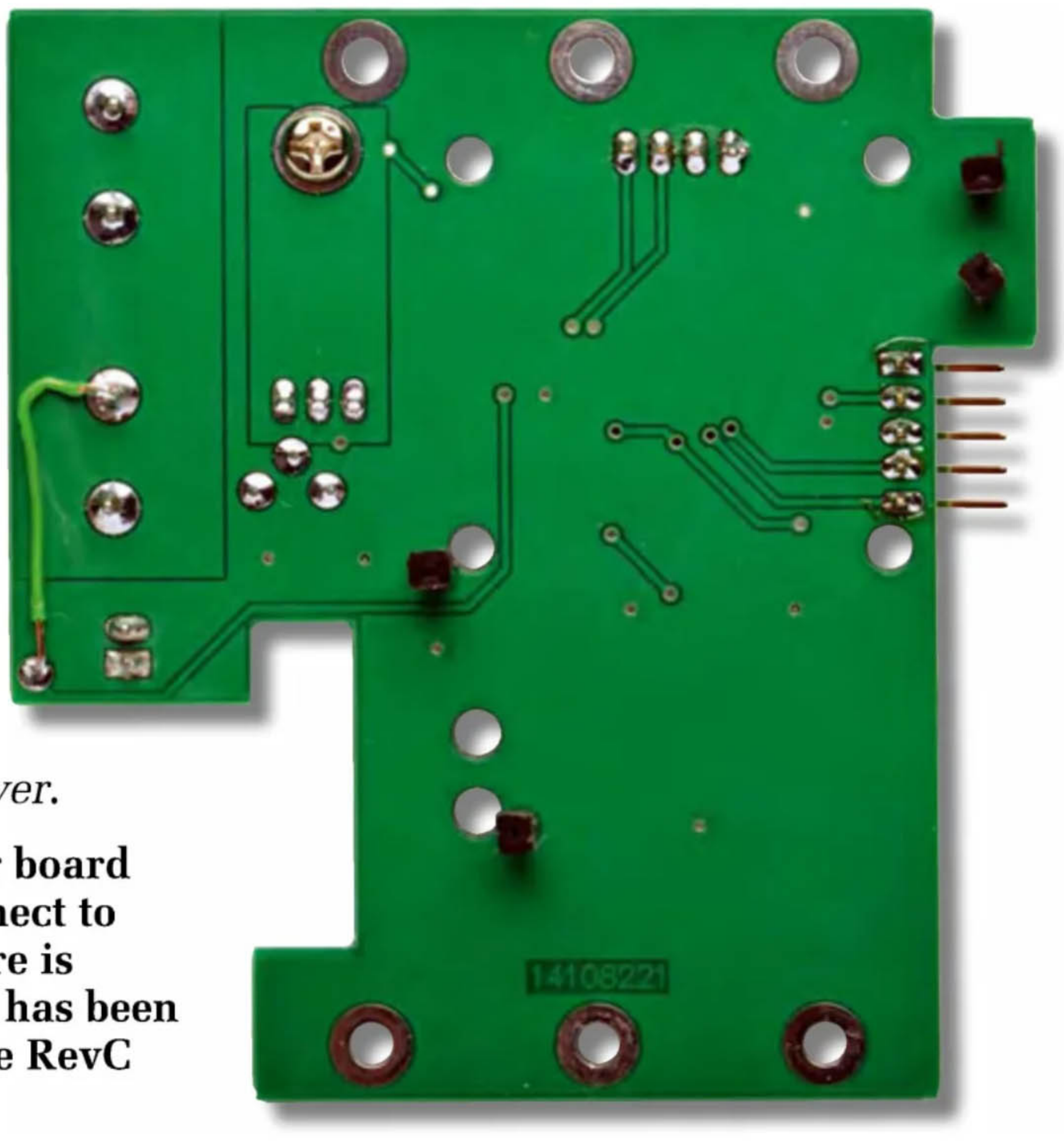
Use four 15mm machine screws to secure four 10mm tapped spacers facing up from the *Driver* PCB that correspond to the 'corner' mounting holes on the *Adaptor*. This will allow the *Adaptor* PCB to rest above the *Driver*.

Now solder the four single header pins to TP2, TP3, TP5 and TP7 so they face out of the top of the *Driver* PCB. We'll do these male headers first because they are much easier to install squarely.

Slot the single pin sockets onto those newly soldered pins. It's expected that they don't push all the way down. Rest the *Adaptor* PCB over the screws and pins and ensure that the pins come out through the test points on the *Adaptor* PCB, then solder the sockets to the *Adaptor* PCB.

If you need to separate the two PCBs, do so with care and also be sure to align the headers when reconnecting to avoid bending them.

Now run two short lengths of 10A-rated wire between CON2 on the



The underside of the Adaptor board showing the sockets that connect to the test points. The added wire is because it is a prototype; this has been replaced by a PCB trace in the RevC version.

Driver PCB and CON3 on the *Adaptor* PCB, being sure to connect with the correct polarity according to the PCB silkscreen. You can see the colour coding in our photos.

Reconnect the OLED module and thermistor and secure the *Adaptor* PCB with the four 15mm tapped spacers into the exposed upwards-facing threads. The acrylic cover piece is fitted after commissioning and setup.

Commissioning and calibration

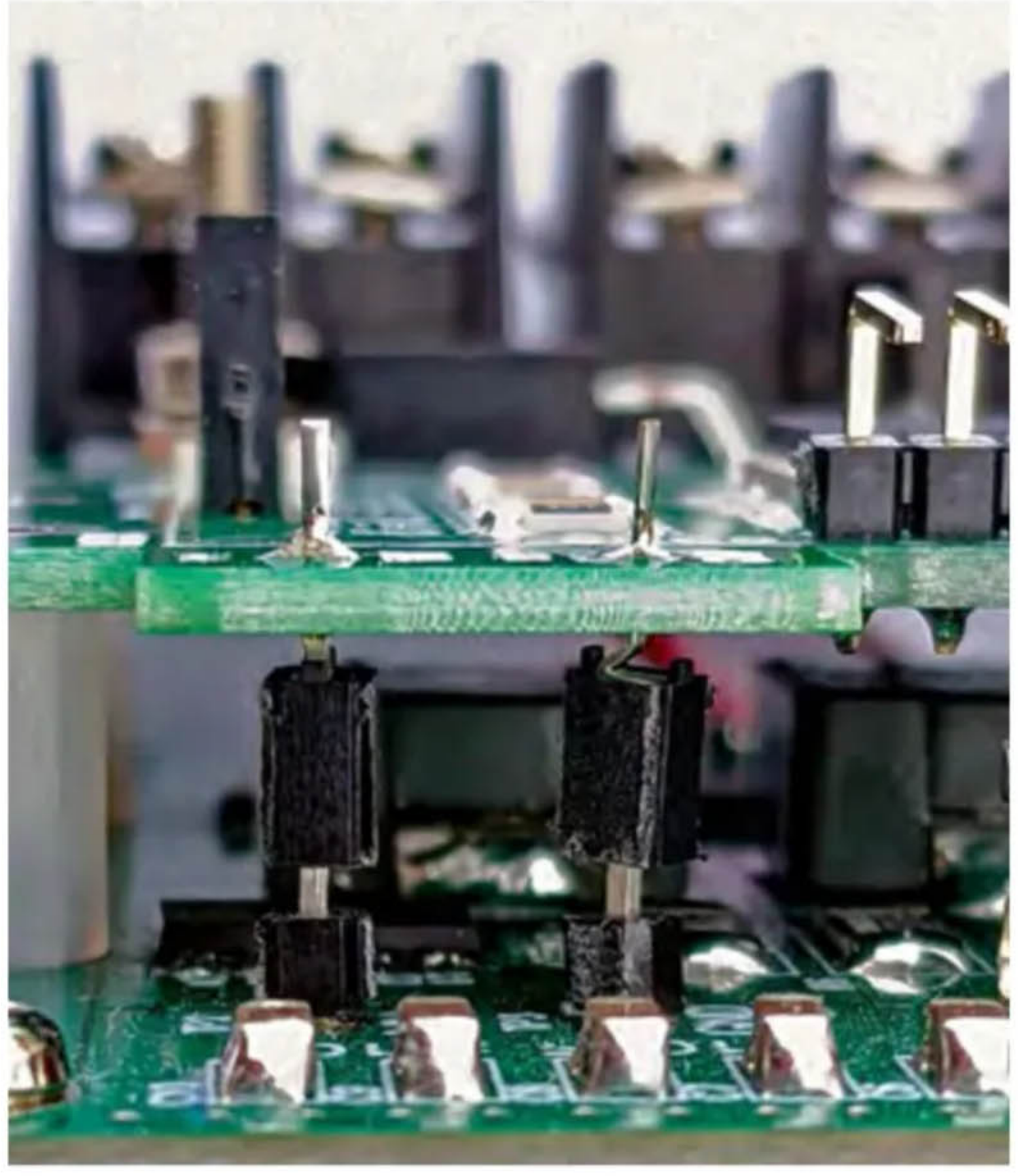
Start by connecting your power supply to CON1, paying attention to the polarity. The OLED should spring to life and display FLOAT mode after a few seconds. To conserve power, it's only updated about once per second unless one of the buttons is pressed.

This is the main status page; you can access the remaining configuration pages by pressing S3 to cycle through. It's a good idea to leave the main status page active as the other pages will not allow the display to blank when the supply is disconnected.

Even though no battery is connected, the diode will cause a voltage to be present at CON4, where the battery voltage is measured. With no battery connected, the current should be close to zero, probably showing 0.01A due to the internal draw of the *Adaptor* PCB.

Press and hold S1 for two seconds until the BULK/ABS mode starts. You should see the voltage increase above its FLOAT value. The BULK/ABS mode should run for ten seconds until it detects that no current is flowing due to no battery being present. You can stop BULK/ABS charging anytime by pressing the S2 button on the main page; this will also end storage charging.

The default temperature coefficient is zero, so you will need to change the value to test this feature. A negative value means that an increase in temperature will cause a decrease in voltage, and the change will be quite small.



This shows more clearly the connection arrangement between the Adaptor PCB and the Driver PCB.

There are four calibration parameters that can be adjusted if necessary, although the defaults should be perfectly functional. Press S3 to cycle through the configuration pages. The first four are to set calibration constants, while the next 12 set various operating parameters. Two further pages are used to activate and save the various settings.

Table 1 summarises the configuration pages. The four calibration constants are displayed alongside their calculated values.

This means they can be calibrated using a multimeter to measure the actual value. The calibration constant is then adjusted until the multimeter value matches the displayed value. These constants are simple multipliers, so increasing the constant will increase the calculated value.

If calibrating the current in this way, you will need to ensure there is a load on the *Driver* so that the proportions are meaningful.

Adjust these as needed, then cycle through to the 'Use Edits' page and press S1; the 'Loaded' message should appear. Then press S3 once more and press S1 again to save the settings to Flash memory; you should see the message 'Saved'.

Voltage and current settings

Dial in your desired Float voltage using the voltage trimpot on the *Driver*. Diode D6 will drop some voltage, even at low currents, so you'll want to tweak this later. Setting the voltage 0.3V higher is a safe starting point and can be adjusted later when a battery is connected.

Adjust the current to your desired maximum using the trimpot on the *Driver*. Remember that the minimum is around 2A, and the maximum is around 8A, at the ¾ position of the trimpot. Anything above the ¾ position will disable current limiting and is probably not a suitable setting for the *Charger*.

Remember also that the current will creep higher at lower output voltages. Refer to the *Driver* article for details or run some tests with a deeply discharged battery to check this. You can also adjust this later. A good time will be when a flat battery is first connected to the *Charger*, as this is a typical maximum load condition.

The other *Adaptor* settings will be fine for a typical lead-acid 12V battery but will need to be changed for a 24V battery. For example, change the low-voltage alarms if using a 24V battery. In general, the Low Battery, Low Output and Bulk Start voltages should be altered to suit a 24V battery by doubling them.

The Wikipedia article on IUoU charging (which is the DIN designated name for this type of charging) has several suggested settings. For more details, see **https://w.wiki/5SR9**

Table 2 also has some suggested values for specific parameters related to the *Charger*.

As we mentioned, we've picked some pretty conservative values to start with. You may need to switch to more aggressive values if your batteries will see heavy use. The storage mode is disabled by default but should be enabled for batteries that see infrequent use.

The bulk/absorption time will depend on the current and battery capacity. Keep in mind that these phases can contribute up to 80-90% of the total charge delivered. This depends on the bulk/absorption start voltage; the 80% figure for bulk charging only applies to a very flat battery.

The temperature coefficient does not need changing when switching between 12V and 24V batteries as it is a proportion of the charge voltage. The default value is zero, which means no correction occurs. That's ideal for LiFePO$_4$ batteries, but you should set it to the manufacturer's suggested value for lead-acid batteries to ensure proper charge termination.

Typical values around 0.15%/°C correspond to 3.6mV/°C per 2.4V cell, and you can also see suggested values in Table 2.

In float, bulk/absorption and storage modes, a timer is shown in the bottom right-hand corner of the display. This will count down to the following timed state change, to the float state for bulk/absorption and storage modes.

In float mode, the timer counts down to storage mode if it is enabled. If storage mode is disabled, no timer will be seen on the float page.

If there is a power-off error, the timer is the number of seconds until the screen blanks to save power. You can press any button to enable the screen again and reset this timer.

Battery charging

You can connect the battery now that the float charge settings have been configured. Depending on the settings, bulk charging may start.

This is a good time to check that D6's heatsinking is adequate, as bulk charging is typically the time of highest current draw.

Ideally, you should let the battery charge fully. Recall that you can

Table 1: Charger settings pages

Title	Function	Notes	Defaults
BATTERY V	Battery voltage (CON4) calibration constant	These pages also display the calculated voltage/current based on the calibration constant. These are best adjusted by using S1/S2 to adjust the constant while comparing the calculated value to a multimeter reading until the two match.	
SUPPLY V	Supply voltage (CON1) calibration constant		
OUTPUT V	Output voltage (CON3) calibration constant	Note that you will need a reasonable load (eg, a flat battery) to calibrate the current, and you should adjust for the Adaptor using around 10mA internally.	
OUTPUT I	Driver current (from CON2 to CON3) calibration constant		
LOW V BAT	Low battery voltage error threshold	If any voltage is measured below its LOW threshold, the Charger enters an alarm state and stops all bulk, absorption and storage charging. An error is displayed on the main page.	11.0V
LOW V SUP	Low supply voltage error threshold		11.0V
LOW V OUT	Low output voltage error threshold		11.0V
BULK START	Voltage below which bulk charging is triggered	These parameters determine the operation of the bulk and absorption modes. A timer also determines the maximum time that bulk charging will operate (see below).	12.0V
BULK END	The current below which bulk charging stops		0.5A
BULK BOOST	The amount by which the output voltage is increased (above float voltage) in bulk mode		4%
STORE DROP	The amount by which the output voltage is decreased in storage mode	The 4.5% value is based on a per-cell reduction from 2.3V to 2.2V. Higher values up to 10% may completely stop charging.	4.5%
BULK TIME	The maximum time that bulk charging runs for	Assuming the bulk current limit has not been reached, bulk charging will run for this period (in hours and minutes). If bulk charging is interrupted by a low supply voltage, the remaining bulk time will slowly ramp back up to this limit until bulk charging recommences.	2:00 hours (HH:MM)
STORE TIME	The time for which storage charging occurs	Apart from pressing S2 on the main page or a low voltage error, this timer expiring is the only condition that will end storage charging.	144:00 hours (<1 week)
STORE DELAY	The time between consecutive storage charges	This timer is reset when float charging begins and counts down as long as no error or other state change occurs. If this is set to zero, no storage charging occurs.	0:00 hours (off)
TEMP COEFF	Battery voltage temperature coefficient	It's recommended that the battery float charge be modified at different temperatures. This parameter sets the change from nominal at 25°C.	0%/°C
Use Edits	Either load or discard the edited settings values	Changes made to parameters do not affect charging until you press S1 on this screen. (Pressing S2 instead discards the changes and thus reverts to the previous settings.)	
Save Flash	Save current setting to Flash memory	Pressing S1 will save the current values in use to Flash memory so that they will be loaded at power-up.	

manually trigger bulk/absorption cycles if necessary. This will allow you to tweak the *Driver's* voltage setting trimpot to account for the drop across the diode.

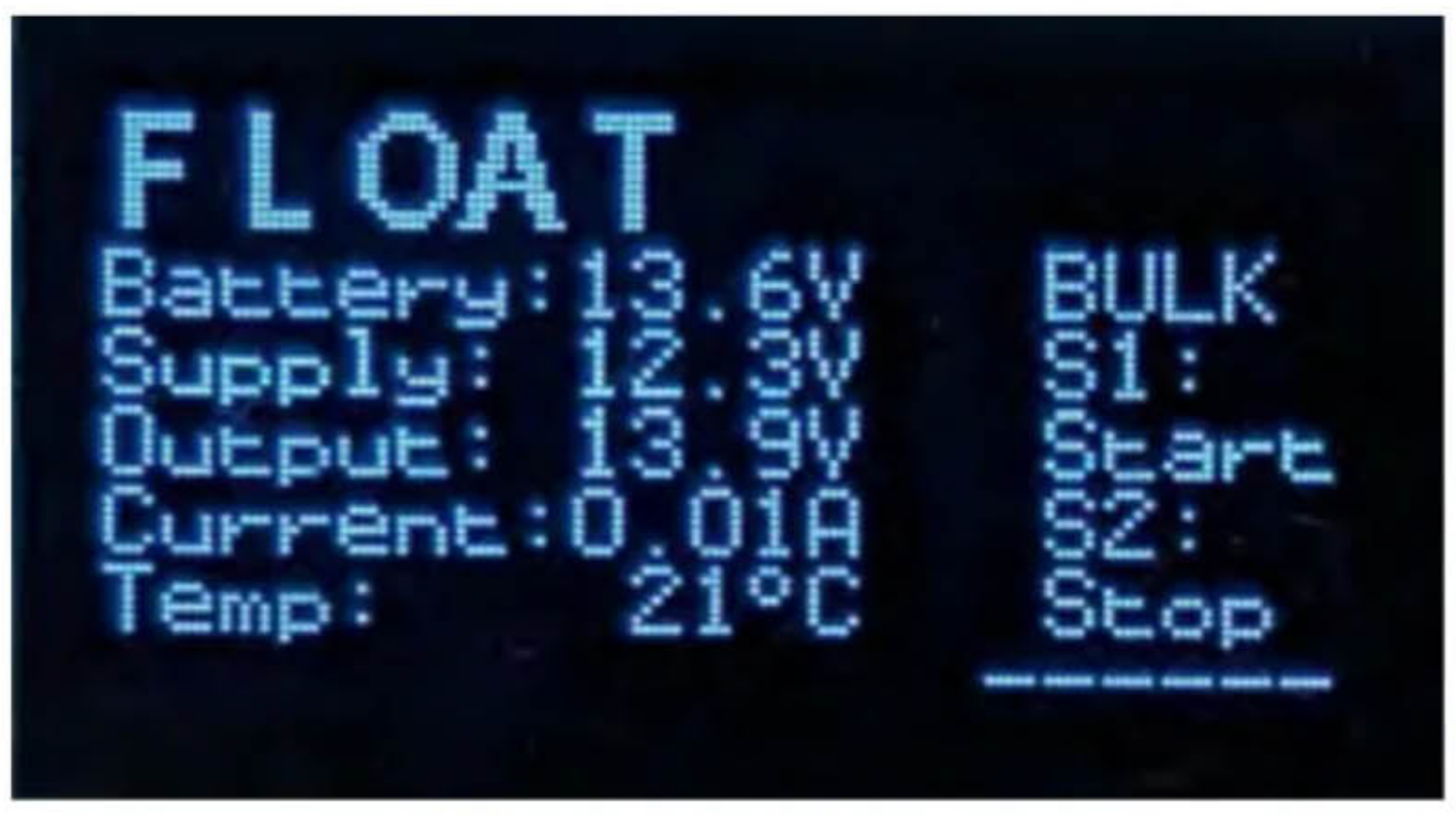
If possible, let the battery run down to permit bulk/absorption charging from a flat state. Doing this will allow you to adjust the bulk/absorption boost percentage.

Conclusion

Once the *Charger* has been set up, the acrylic cover piece can be placed over the spacers and secured with the last four screws. Note that there are holes in the cover piece to allow occasional access to the buttons.

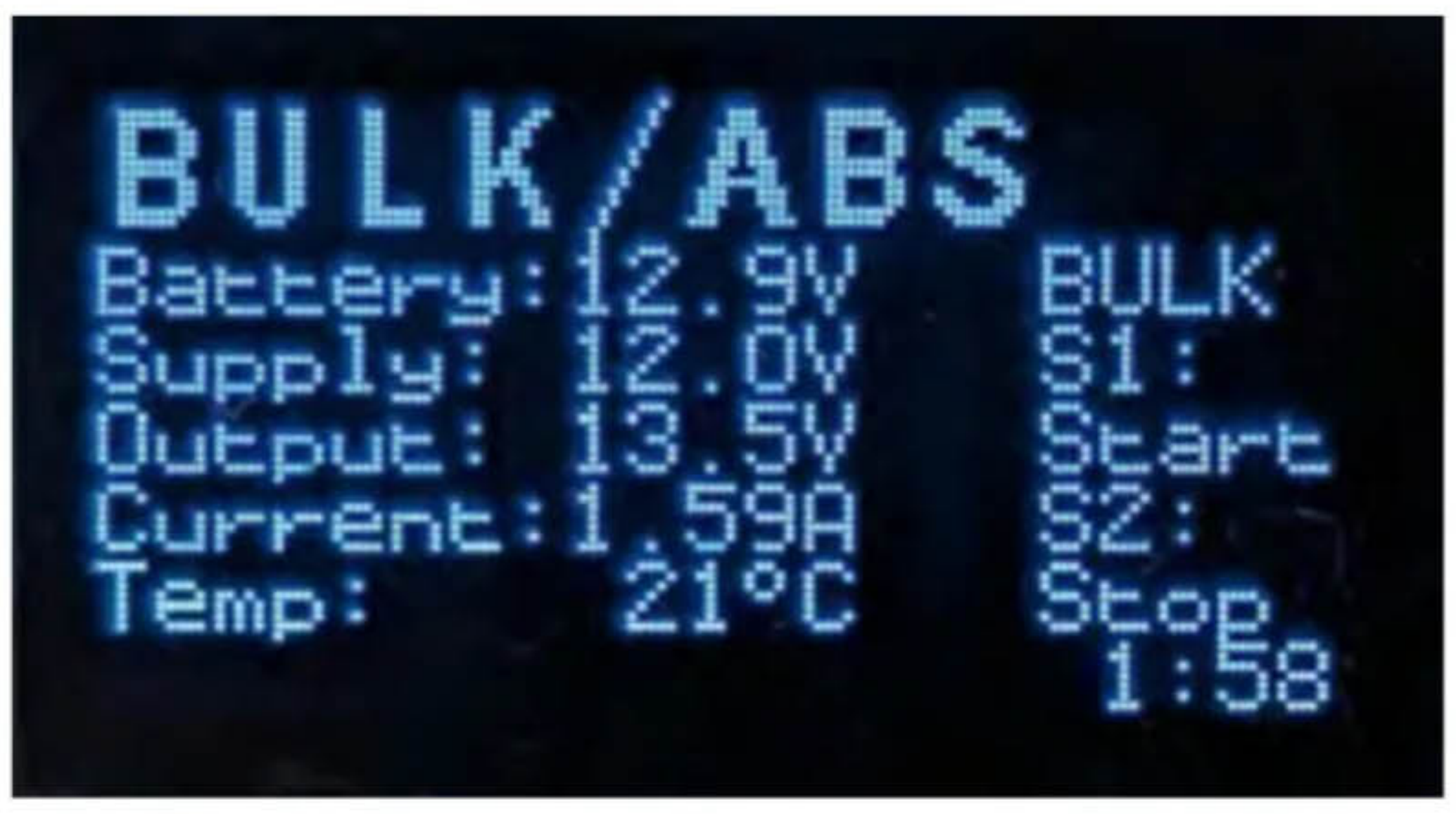
If you need to mount the *Charger*, then you can either use the four tapped spacers at the rear, or the four at the front if you have a clear panel or bezel.

The *Driver* is a versatile board that is handy for producing a wide range of voltages at useful current levels. The addition of the *Adaptor* PCB turns it into a versatile *Battery Charger*. The *Charger* is highly configurable and can be used to work with many different types of batteries.



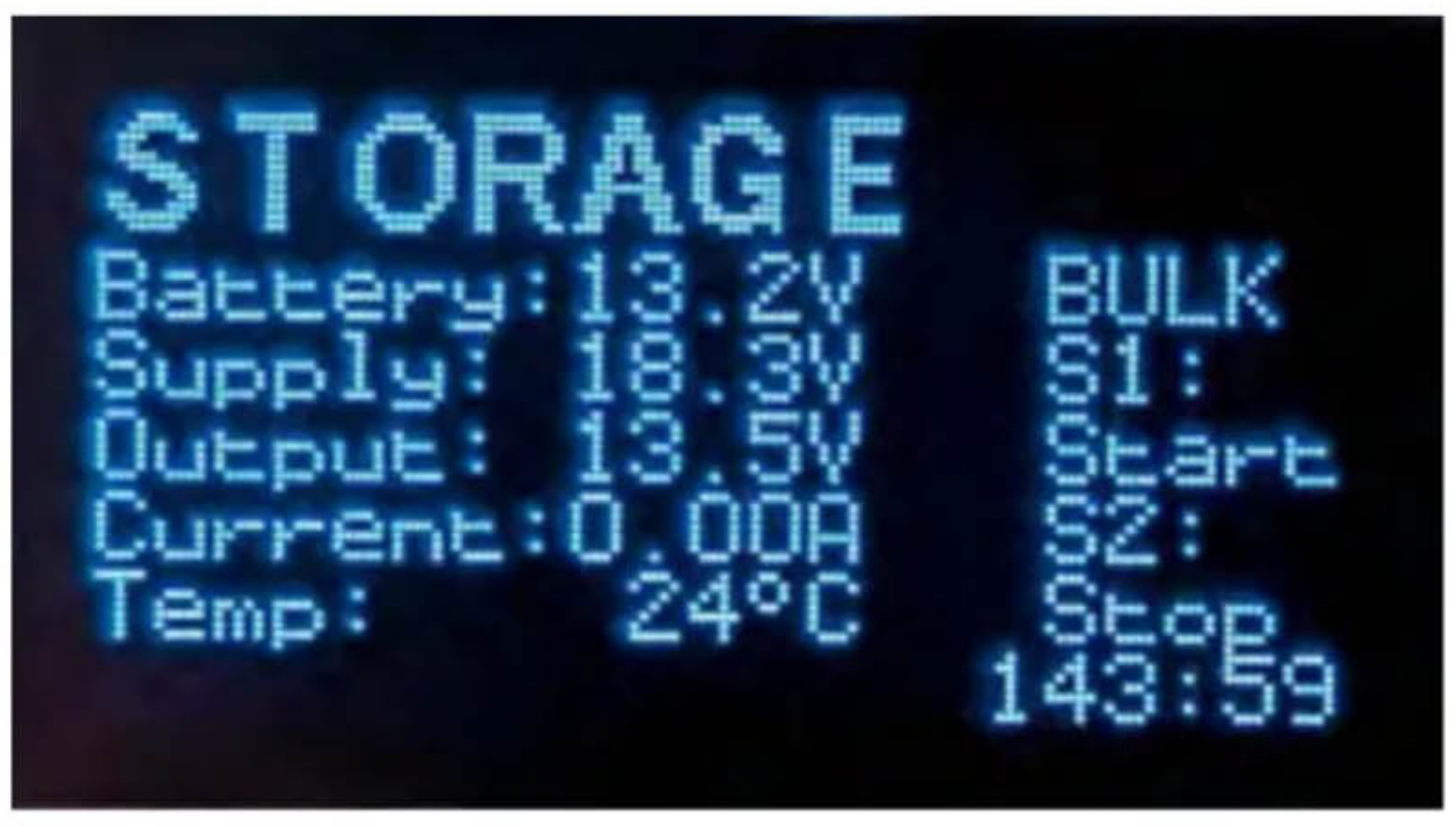
```
FLOAT
Battery:13.6V   BULK
Supply: 12.3V   S1:
Output: 13.9V   Start
Current:0.01A   S2:
Temp:    21°C   Stop
                ------
```

Screen 1: when everything is operating normally, you should see this screen. The Adaptor is not modifying the output voltage and based on the current displayed, the battery is floating in a fully charged state. (Dashes lower right indicate that Storage mode is disabled.)



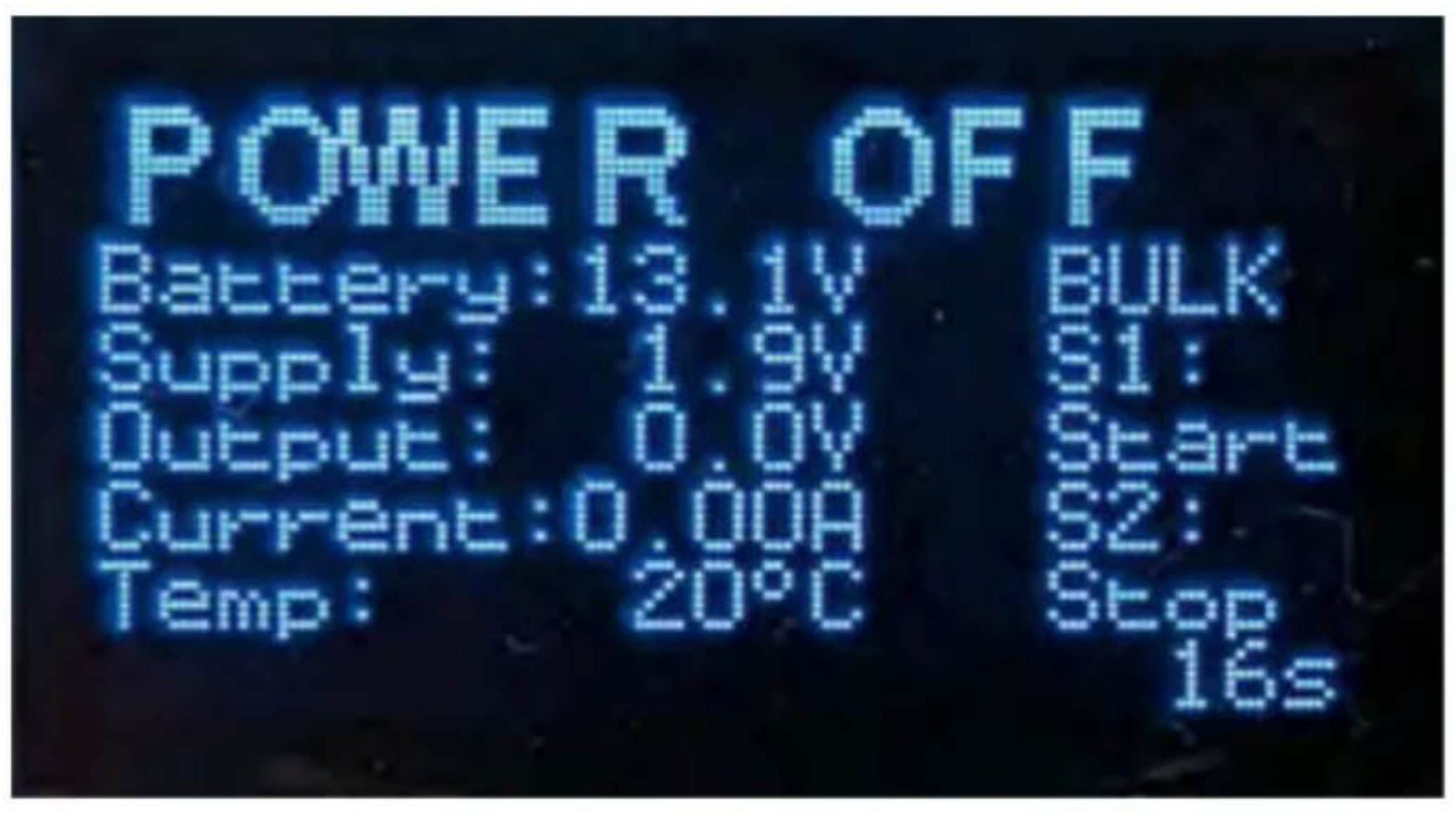
```
BULK/ABS
Battery:12.9V   BULK
Supply: 12.0V   S1:
Output: 13.5V   Start
Current:1.59A   S2:
Temp:    21°C   Stop
                  1:58
```

Screen 2: during Bulk charging, the Adaptor increases the output voltage. In this case, the Driver has current limiting active, which results in a lower output voltage than in Screen 1. The timer at lower right indicates the maximum remaining Bulk charging time.



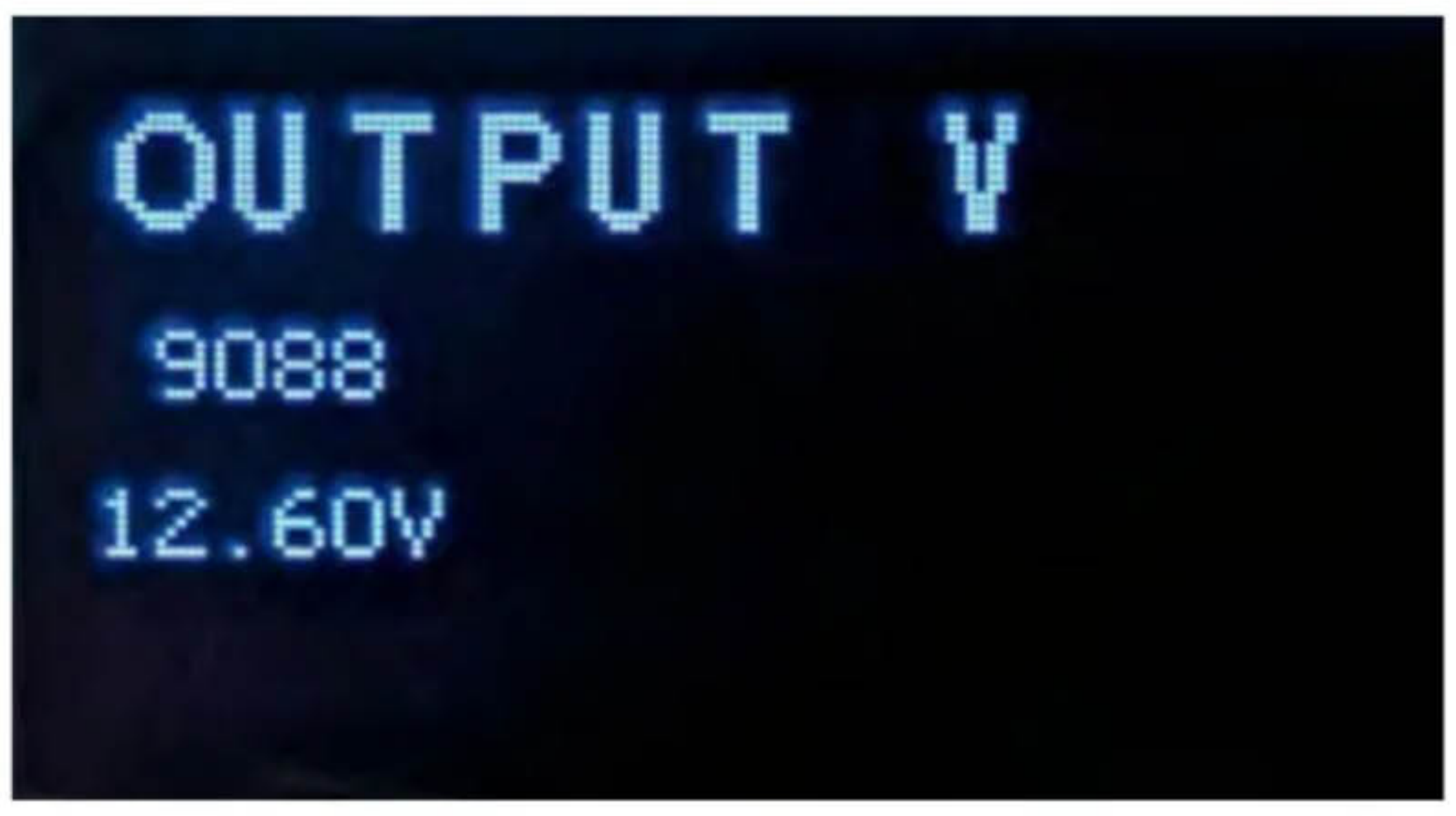
```
STORAGE
Battery:13.2V   BULK
Supply: 18.3V   S1:
Output: 13.5V   Start
Current:0.00A   S2:
Temp:    24°C   Stop
              143:59
```

Screen 3: the output voltage is reduced below the Float voltage in Storage mode, and minimal current will flow into the battery, just enough to stop it from discharging. Either Bulk or Storage modes can be cancelled by pressing S2.



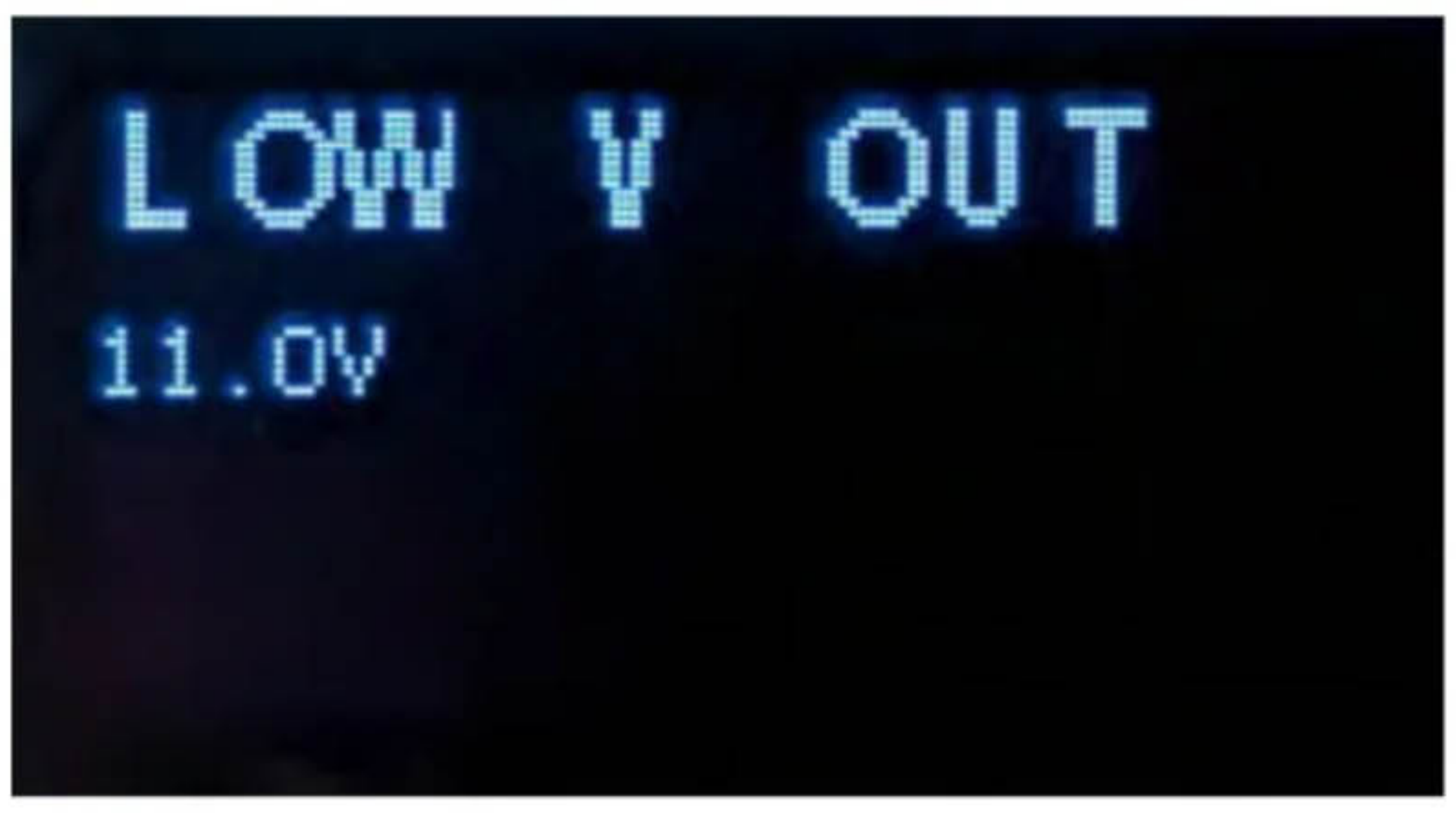
```
POWER OFF
Battery:13.1V   BULK
Supply:  1.9V   S1:
Output:  0.0V   Start
Current:0.00A   S2:
Temp:    20°C   Stop
                   16s
```

Screen 4: you will see this screen if the power supply is off or disconnected. The output voltage is low and the displayed current is 0.00A. The counter at lower right counts down until the screen blanks; you can reactivate it by pressing any button.



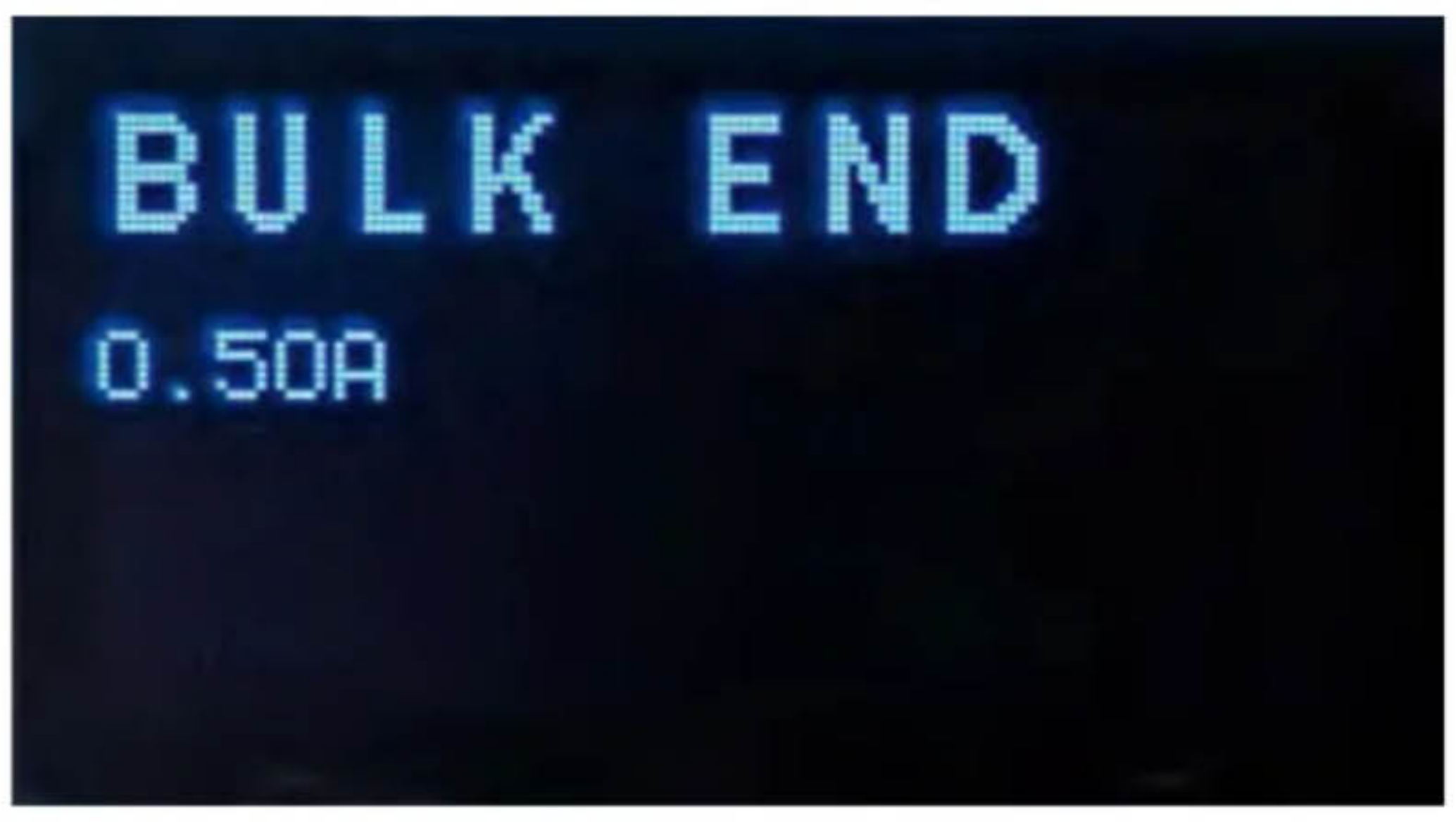
```
OUTPUT V
 9088
12.60V
```

Screen 5: calibration constants for the three voltages and the current value displayed on the main screen can be adjusted on these pages via buttons S1 and S2. The newly calculated value is displayed and can be compared to a reading from a multimeter.



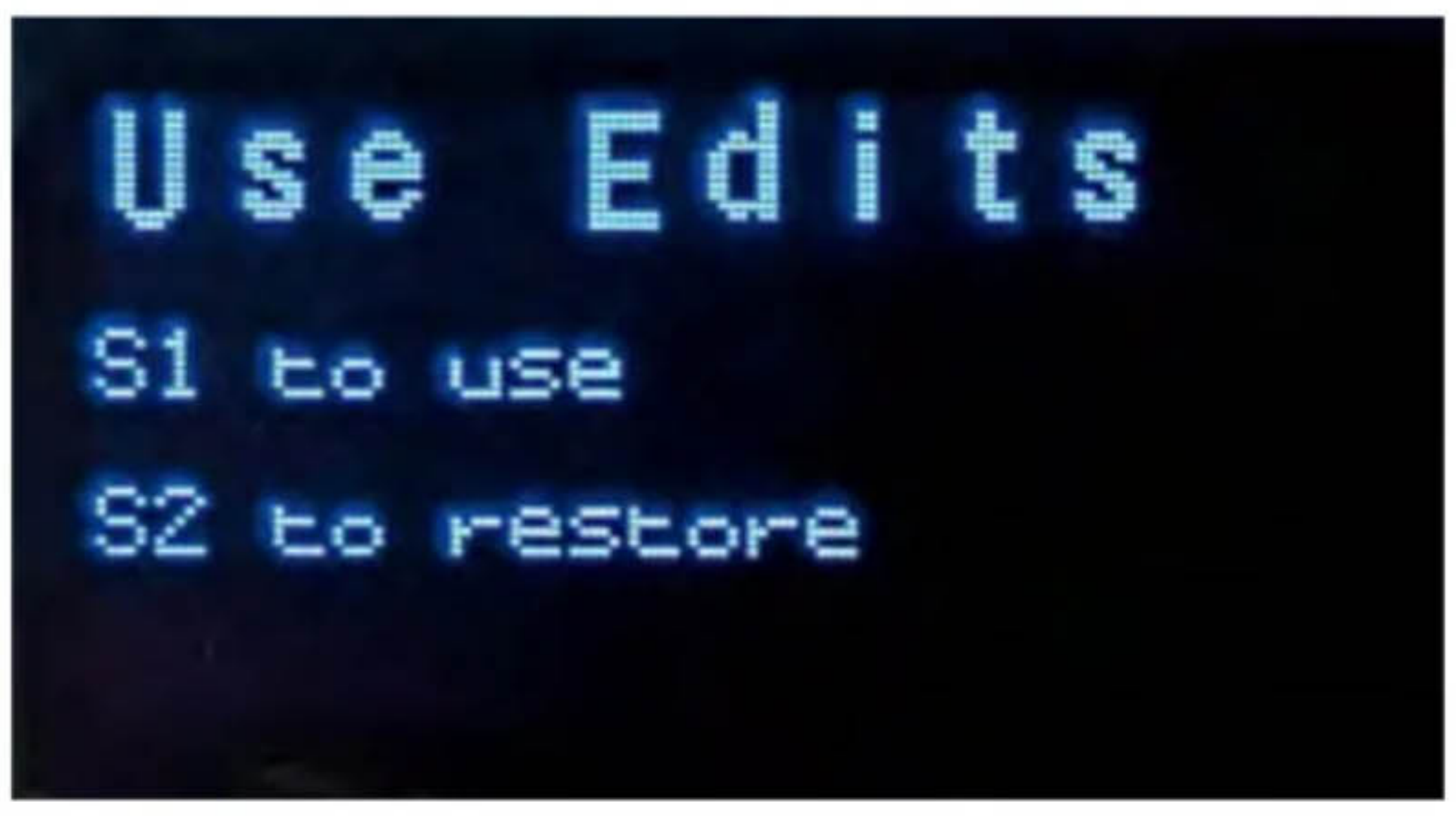
```
LOW V OUT
11.0V
```

Screen 6: several voltage thresholds can be set. There are three alarm thresholds and a Bulk charging start threshold. Each press of S1 or S2 changes the value by 0.1V, or you can hold the buttons to speed through the values.



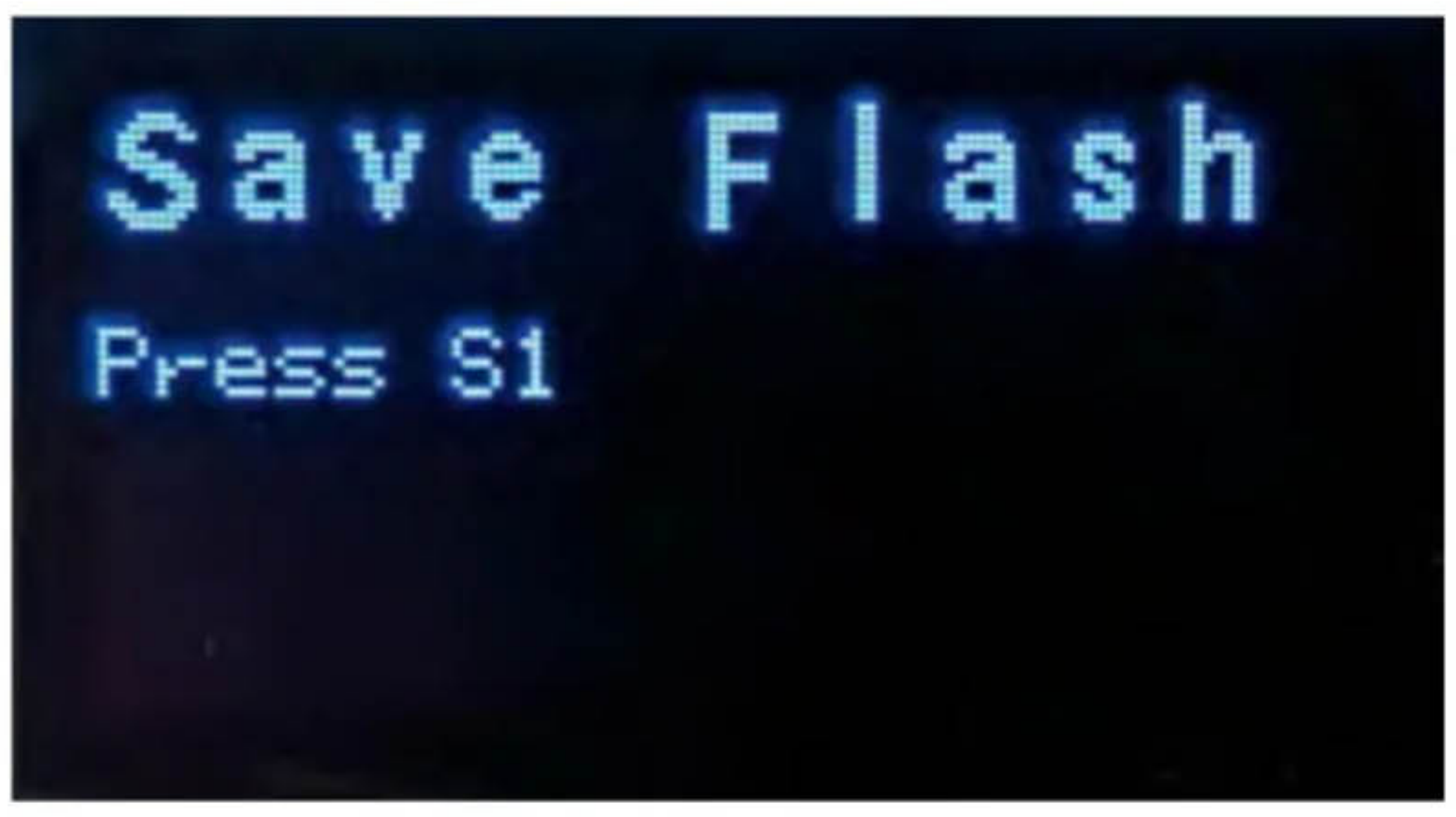
```
BULK END
0.50A
```

Screen 7: the single current threshold is the trigger for ending Bulk charging and is adjusted on this page. This is changed with S1 and S2 in increments of 0.05A (50mA).



```
Use Edits
S1 to use
S2 to restore
```

Screen 8: none of the changes made on the preceding pages are used immediately but can be activated by pressing S1 on this screen. S2 reverts the edited values. The text on this screen will change to indicate when a button has been pressed.



```
Save Flash
Press S1
```

Screen 9: changes are not automatically saved to Flash memory. Pressing S1 on the Save Flash screen stores the active settings to flash memory so that they will be loaded as the defaults on the next power-up.

Table 2: suggested settings (check manufacturer's recommendations)

Battery Type	SLA 12V	AGM / Flooded lead-acid 12V	$LiFePO_4$ 12V	SLA 24V	AGM / Flooded lead-acid 24V	$LiFePO_4$ 24V
Float voltage (Driver trimpot)	13.5V	13.8V	12.6V	27.0V	27.6V	25.2V
LOW V BAT/ OUT	11.0V	11.0V	11.0V	22.0V	22.0V	22.0V
BULK START	12.0V	12.0V	12.0V	24.0V	24.0V	24.0V
BULK BOOST	4%	4%	10%	4%	4%	10%
TEMP COEFF	-0.17%/°C	-0.14%/°C	0%/°C	-0.17%/°C	-0.14%/°C	0%/°C

Fluke/Philips PM3092 Oscilloscope
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IFR 2948B	Communication Service Monitor Opts 03/25 Avionics	POA
IFR 6843	Microwave Systems Analyser 10MHz – 20GHz	POA
R&S APN62	Syn Function Generator 1Hz – 260kHz	£295
Agilent 8712ET	RF Network Analyser 300kHz – 1300MHz	POA
HP8903A/B	Audio Analyser	£750 – £950
HP8757D	Scaler Network Analyser	POA
HP3325A	Synthesised Function Generator	£195
HP3561A	Dynamic Signal Analyser	£650
HP6032A	PSU 0-60V 0-50A 1000W	£750
HP6622A	PSU 0-20V 4A Twice or 0-50V 2A Twice	£350
HP6624A	PSU 4 Outputs	£400
HP6632B	PSU 0-20V 0-5A	£195
HP6644A	PSU 0-60V 3.5A	£400
HP6654A	PSU 0-60V 0-9A	£500
HP8341A	Synthesised Sweep Generator 10MHz – 20GHz	£2,000
HP83630A	Synthesised Sweeper 10MHz – 26.5 GHz	POA
HP83624A	Synthesised Sweeper 2 – 20GHz	POA
HP8484A	Power Sensor 0.01-18GHz 3nW-10µW	£75
HP8560E	Spectrum Analyser Synthesised 30Hz – 2.9GHz	£1,750
HP8563A	Spectrum Analyser Synthesised 9kHz – 22GHz	£2,250
HP8566B	Spectrum Analsyer 100Hz – 22GHz	£1,200
HP8662A	RF Generator 10kHz – 1280MHz	£750
Marconi 2022E	Synthesised AM/FM Signal Generator 10kHz – 1.01GHz	£325
Marconi 2024	Synthesised Signal Generator 9kHz – 2.4GHz	£800
Marconi 2030	Synthesised Signal Generator 10kHz – 1.35GHz	£750
Marconi 2023A	Signal Generator 9kHz – 1.2GHz	£700

Marconi 2305	Modulation Meter	£250
Marconi 2440	Counter 20GHz	£295
Marconi 2945/A/B	Communications Test Set Various Options	POA
Marconi 2955	Radio Communications Test Set	£595
Marconi 2955A	Radio Communications Test Set	£725
Marconi 2955B	Radio Communications Test Set	£800
Marconi 6200	Microwave Test Set	£1,500
Marconi 6200A	Microwave Test Set 10MHz – 20GHz	£1,950
Marconi 6200B	Microwave Test Set	£2,300
Marconi 6960B	Power Meter with 6910 sensor	£295
Tektronix TDS3052B	Oscilloscope 500MHz 2.5GS/s	£1,250
Tektronix TDS3032	Oscilloscope 300MHz 2.5GS/s	£995
Tektronix TDS3012	Oscilloscope 2 Channel 100MHz 1.25GS/s	£450
Tektronix 2430A	Oscilloscope Dual Trace 150MHz 100MS/s	£350
Tektronix 2465B	Oscilloscope 4 Channel 400MHz	£600
Farnell AP60/50	PSU 0-60V 0-50A 1kW Switch Mode	£300
Farnell XA35/2T	PSU 0-35V 0-2A Twice Digital	£75
Farnell AP100-90	Power Supply 100V 90A	£900
Farnell LF1	Sine/Sq Oscillator 10Hz – 1MHz	£45
Racal 1991	Counter/Timer 160MHz 9 Digit	£150
Racal 2101	Counter 20GHz LED	£295
Racal 9300	True RMS Millivoltmeter 5Hz – 20MHz etc	£45
Racal 9300B	As 9300	£75
Solartron 7150/PLUS	6½ Digit DMM True RMS IEEE	£65/£75
Solatron 1253	Gain Phase Analyser 1mHz – 20kHz	£600
Solartron SI 1255	HF Frequency Response Analyser	POA
Tasakago TM035-2	PSU 0-35V 0-2A 2 Meters	£30
Thurlby PL320QMD	PSU 0-30V 0-2A Twice	£160 – £200
Thurlby TG210	Function Generator 0.002-2MHz TTL etc Kenwood Badged	£65

HP/Agilent HP 34401A Digital
Multimeter 6½ Digit £325 – £375

HP33120A	Function Generator 100 microHz – 15MHz	£350
HP53131A	Universal Counter 3GHz Boxed unused	£600
HP53131A	Universal Counter 225MHz	£350
Audio Precision	SYS2712 Audio Analyser – in original box	POA
Datron 4708	Autocal Multifunction Standard	POA
Druck DPI 515	Pressure Calibrator/Controller	£400
Datron 1081	Autocal Standards Multimeter	POA
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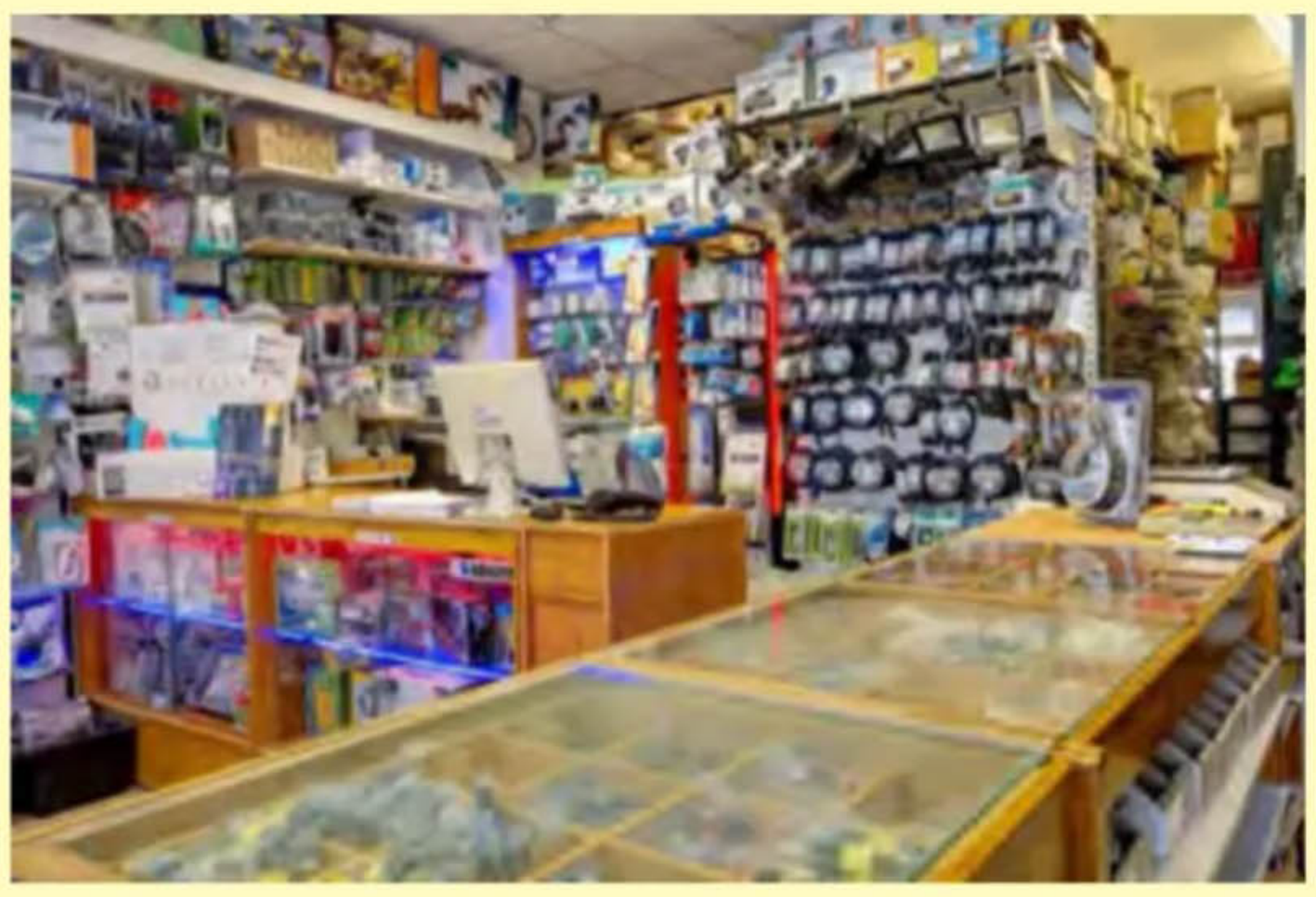

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NEW

PIC & AVR Chips from Microchip

By Tim Blythman

The parts shortages in recent years have given us the incentive to look more widely for alternatives to the parts we've been using. Microchip Technology offered to send us samples of new microcontrollers and, as newer chips tend to have more features at a lower cost, we were keen to find out what the new parts bring.

Searches for alternative parts are now something we do far too often. Microcontrollers have been some of the worst affected parts (along with MOSFETs), but other ICs and even some passives are becoming harder to find.

Many of our favourite microcontrollers from years past are falling out of favour as newer, cheaper parts appear. The older PIC and AVR parts haven't been discontinued, but as manufacturers cannot keep up with demand, they are allocating more resources to making the latest parts. As a result, many of the older chips have become scarce.

However, every cloud has a silver lining, and many of the newer parts are much more capable than their predecessors. Many are also 'drop-in replacements', at least in terms of having the same pin allocations.

Recently, in new projects, we have written about the new range of 8-pin Microchip devices. They are the PIC16F1521**3** and PIC16F1521**4**, about the cheapest 8-pin, 8-bit PICs available. Despite that, they have more features than the earlier 8-pin parts we used, like the PIC12F**675** and PIC12F**1572**.

You may also be aware of the new PIC16F171xx series of parts, which includes (among many other features) a handy 12-bit analogue-to-digital converter (ADC) peripheral. The PIC16F17146 is from Farnell, Digi-Key and others and we obtained a handful to try out.

20-pin chips

Microchip gave us further suggestions and sent sample parts for us to try. We bought some PIC16F18**146** chips ourselves and received free samples of the PIC16F18**045**.

These are all new 20-pin parts in DIL packages (ie, DIP). Other pin counts are available, but we figured that a 20-pin chip is a sweet spot for many applications. Another reason for choosing to try out parts with 20 pins is that this is a bit of a gap in our repertoire; we have tended to use either very small 8-pin chips or larger 28-pin chips.

One 20-pin part we often use is the PIC16F1459. It's handy because it includes a USB peripheral but is relatively inexpensive. Unfortunately, though, three pins are occupied by the USB function, and one cannot be used for any other purpose. The other two can be used as inputs only, even if the USB peripheral is not used.

With the next lower pin count being 14 pins, there is often little call for the PIC16F1459 unless the USB function is needed. So we figured it was time to see if there were other options for parts around this size.

The next step above a 20-pin micro is usually 28 pins but they are pretty bulky, especially in DIP.

There are other advantages for the 20-pin parts; for example, the PPS (peripheral pin select) feature can be used to remap all digital pins on 20-pin and smaller parts, but not on larger parts.

Smaller parts

To continue our theme of 8-pin parts from previous articles, we took up Microchip's offer of a sample of the PIC16F18**015**. It is from the same family as the PIC16F18**045** and has much the same complement of peripherals, although they are exposed on fewer pins, so it's likely they can't all be used simultaneously.

So we have a good range which should provide some interesting comparisons both between families and between members of the same family. We can also draw some comparisons to the other 8-pin PICs.

Currently, the PIC16F18015 also appears to be the cheapest 8-pin 8-bit PIC microcontroller with the most RAM and Flash memory, at 1kiB of RAM and 14kiB of Flash.

The upcoming (at the time of writing) PIC16F**17115** and PIC16F**18115** will have similar quantities of RAM

The five subjects of this review include a new 8-pin PIC, three new 20-pin PICs from different families and a 32-pin AVR microcontroller. They all have a slew of interesting features. From left to right, they are: PIC16F18015, PIC16F18045, PIC16F18146, PIC16F17146 and AVR64DD32.

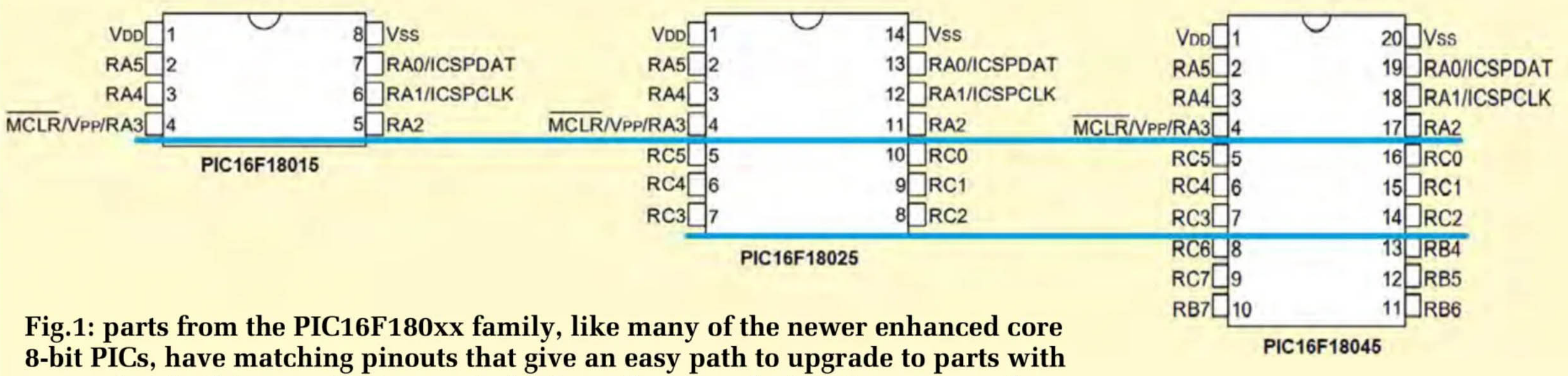


Fig.1: parts from the PIC16F180xx family, like many of the newer enhanced core 8-bit PICs, have matching pinouts that give an easy path to upgrade to parts with more pins. In this case, the topmost pins have the same designations across the 8-pin PIC16F18015, the 14-pin PIC16F18025 and the 20-pin PIC16F18045.

and Flash memory. They belong to the same families as the 20-pin parts we are looking at here.

The *Improved SMD Test Tweezers* project (*PE*, May 2023) was only possible because the PIC16F15214 offers an increase in available Flash memory over the PIC12F1572 used in the original Tweezers. That allowed us to add extra features to the firmware.

AVR chips

Microchip's acquisition of Atmel in 2016 has meant that the popular AVR microcontrollers, used extensively in Arduino boards, are now also part of the Microchip stable.

We looked at the ATtiny816 in the July 2021 issue. That article included details on using a PICkit 4 and MPLAB X to program an AVR chip with the tinyAVR core.

We've received samples of some AVR64DD32 chips, part of their latest AVR DD series. One of the more interesting features we read about is MVIO (multi-voltage I/O), which allows some I/O pins to operate at a different voltage than the rest of the chip. We'll get to the AVR64DD32 a bit later.

Cracking the code

One thing that we do like about Microchip's recent 8-bit PIC offerings is that there is a clear path to upgrade to different members of the same family, as well as between different families, due to a high degree of pin compatibility.

The most recent parts, such as those discussed in this article, have five-digit part codes after the PIC16F architecture prefix. Of this code, the first three digits indicate the family. Parts in the same family will have much the same peripheral set.

The fourth digit dictates the number of pins, while the fifth digit reflects the amount of RAM and Flash memory. This is summarised in Tables 1 and 2 for the PIC16F181xx family. Note that the 'kiB' is a unit of 1024 bytes, compared to 'kB', which might refer to 1000 bytes.

While we drew up those tables from the PIC16F181xx data sheet, they seem to fit all recent 8-bit PIC parts with a five-digit suffix. For example, the PIC16F15213 has 256 bytes of RAM and 3.5kiB of Flash memory. We expect the gap between 2 and 4 for the fourth digit is to accommodate 18-pin parts that could substitute for older devices – for example, the PIC16F88.

Compatibility

From the very limited examples we have tested, some parts that share a data sheet will run the same HEX file without problems, as long as it has been compiled for the part with the least RAM and Flash memory. That's because all the critical peripheral registers are in the same locations, and all the peripherals are mapped to the same pins.

There is even a degree of drop-in compatibility between parts in the same family with different pin counts. Fig.1 shows this for members of the PIC16F180xx family. These parts share the same data sheet and have a similar set of peripherals.

You can see how pins 1-8 of the 8-pin part correspond exactly to pins 1-4 and 11-14 of the 14-pin part, with six extra pins corresponding to PORTC being appended as pins 5-10 in between, but physically below the existing PORTA pins. Similarly, the 20-pin parts add more PORTC and PORTB pins without interfering with the relative locations of the existing pins.

What is great about the 20-pin parts is that they offer the PPS (peripheral pin select) feature for all digital pins and peripherals.

That means the digital peripherals can be shuffled around very easily at the software design stage, simplifying hardware design.

Some peripherals appear to change locations between parts, but that would only be a problem for analogue peripherals that cannot be remapped with PPS.

We noted this with some of the earlier enhanced 8-bit parts and our *PIC Programming Helper* from *PE*, June 2022.

The *Helper* uses a 20-pin socket which can work with 8-pin and 14-pin parts due to their similar pinouts, at least in relation to the pins used for programming.

This is straightforward enough for small DIP parts, which all have rows of pins spaced 0.3in (7.62mm) apart. The 20-pin SOIC parts are usually wider than the 8-pin or 14-pin parts, but a drop-in replacement could be made to work with a carefully crafted PCB pad pattern ('footprint') that caters for multiple widths.

You might think that this is pure speculation, but the parts shortage has had us contemplate whether we could supply, for example, a 14-pin SOIC microcontroller in place of an 8-pin SOIC part from the same family.

It is not that bad yet, but our new designs try to keep a few spare millimetres of space to allow that to happen if it's needed in the future!

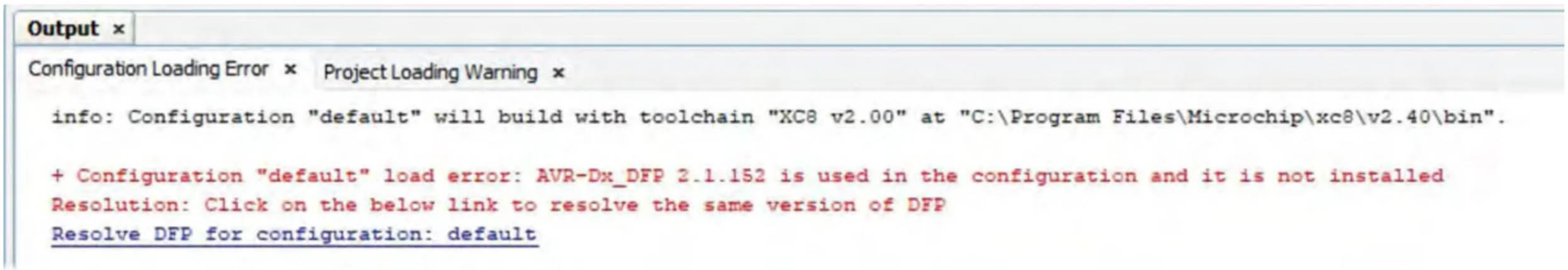
It's worth noting that all the recent PIC families we've seen have followed this trend, meaning that parts

Table 1 – PIC16F181xx pin counts

4^{th} digit	Pin count	# I/O pins
1	8	6
2	14	12
4	20	18
5	28	25
7	40	36

Table 2 – PIC16F181xx memory sizes

5^{th} digit	RAM	Flash
(3)	256B	3.5kiB
4	512B	7kiB
5	1kiB	14kiB
6	2kiB	28kiB



```
info: Configuration "default" will build with toolchain "XC8 v2.00" at "C:\Program Files\Microchip\xc8\v2.40\bin".

+ Configuration "default" load error: AVR-Dx_DFP 2.1.152 is used in the configuration and it is not installed
Resolution: Click on the below link to resolve the same version of DFP
Resolve DFP for configuration: default
```

Screen 1: MPLAB X can now install DFPs (device family packs) to provide device support. If a project is loaded that requires a specific DFP, you can install it by clicking on the blue link. The AVR64DD32 requires the AVR-Dx DFP, which also supports AVR DA and AVR DB series parts.

from different families come close to being drop-in substitutes too, as the power and programming pins are in the same locations.

With the smaller parts having PPS on all pins, purely digital applications should have no trouble being ported between different families with nothing more than minor code changes.

We must admit that the vast range of PICs available can be overwhelming, and we are pretty well spoilt for choice. However, the range narrows somewhat when you limit yourself from choosing parts currently in stock.

MPLAB X v6.00 and new chip support

Earlier this year saw the release of MPLAB X v6.00, a major version jump from the various v5.xx versions that we've been using for the past few years. Unlike the older MPLAB, MPLAB X can be run on Linux and Mac as well as under Windows.

MPLAB X is Microchip's IDE (integrated development environment) for programming their microcontrollers and other devices. An IDE allows programs to be written, compiled and uploaded all using the same application.

Version v5.40 was the first version to only support 64-bit operating systems, so if you are working on an older 32-bit computer, you can only use earlier versions of the IDE, which may not support some of the newer parts that are available.

MPLAB X v5.40 also introduced the concept of DFPs (device family packs). To use the PIC16F1xxxx parts requires a DFP to be installed. That is easily and automatically done through the IDE – see Screen 1.

The 8-bit parts (remember that this includes those parts with a PIC16 prefix) also require a separately installed compiler – known as 'XC8' – which can be downloaded from the Microchip website.

We tried using a previously installed older (v2.20) compiler which gave some warnings about unknown identifiers. An upgrade to XC8 v2.40 removed those warnings.

From our experience, this combination of IDE (MPLAB X v6.00) and compiler (XC8 v2.40) will work best for the newer devices. It's a reasonably large install, with MPLAB X taking almost 9GB and the compiler nearly 2GB of storage space on a Windows machine.

It's possible to install different MPLAB X and compiler versions simultaneously, so you can continue to use older configurations for your other projects.

XC8 v2.40 and other recent versions of the XC8 compiler will also work with supported AVR microcontrollers. These are the 8-bit parts that Microchip took over from Atmel and that Microchip continues to develop.

All our tests on the AVR64DD32 were performed using MPLAB X v6.00 and XC8 v2.40.

If you have not used XC8 before, user guides are available for download. There are separate user guides for PIC and AVR parts, so ensure you are referring to the correct document.

New 20-pin PICs

Table 3 summarises the differences between the new 20-pin parts. It isn't a complete list of the features of these parts, but many of their other peripherals are much the same.

That table is not intended to be a comprehensive list of the features of these parts, but to highlight their differences. All the PIC16F devices use a 14-bit Flash program memory word.

The MPLAB X IDE is the primary programming software to use with Microchip microcontrollers.

The only difference we could see between the PIC16F**17146** and the PIC16F**18146** is that the former has an op amp. Apart from that, they both have a very strong analogue peripheral set.

The Microchip product page for the PIC16F1846 notes that 'It is the first product family to offer the 12-bit differential ADC with computation in low pin count packages.' The parts are recommended for raw sensor applications that require gain and/or filtering, assisted by the new ADC with computation.

The Microchip page for the PIC16F18045 indicates that it is 'for cost-sensitive sensor and real-time control applications.'

All three parts have the following features: zero-cross detect (ZCD), numerically controlled oscillator (NCO), peripheral pin select (PPS) and numerous communication and PWM channels.

As mentioned earlier, PPS allows digital peripheral functions to be mapped to different physical pins. However, parts with more than 20 pins only offer a subset of pins with the PPS feature.

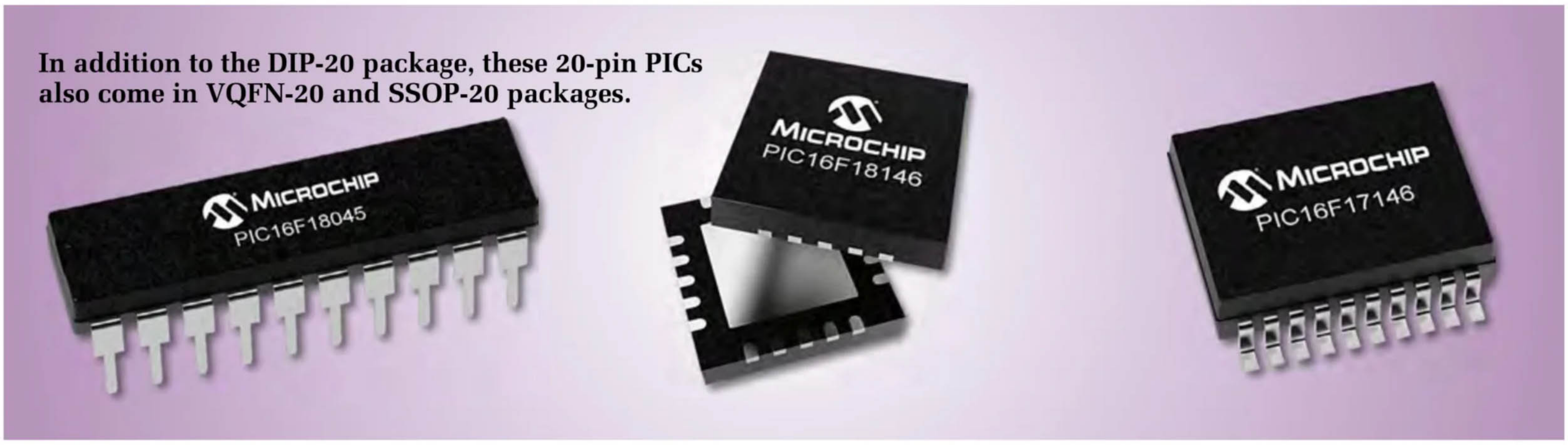
Other features we have seen on many of the newer parts include the Microchip Unique Identifier (MUI).

The PIC16F18045

While the PIC16F18045 clearly has fewer features than the PIC16F**17146** and PIC16F**18146**, it is still better-endowed than members of the PIC16F152xx family.

Since the PIC16F180**15** and PIC16F180**45** share the same data sheet, much of the following applies to the PIC16F18015 as well. The data sheet notes that their complement of peripherals is much the same, although there are fewer pins available on the PIC16F18015 for using them simultaneously.

The PIC16F180**45** (or PIC16F180**15**) includes a complementary waveform



In addition to the DIP-20 package, these 20-pin PICs also come in VQFN-20 and SSOP-20 packages.

generator and four configurable logic cells (CLCs). There are two fixed-voltage references (FVRs), a comparator and a zero crossing detector (ZCD), adding to the ADC among the analogue peripherals.

The FVRs offer 1.024V, 2.048V or 4.096V, subject to an adequate supply voltage. One can be used by the comparator and DAC, the other as a reference or input to the ADC.

While the FVR voltages may vary up to 4% from nominal, their measured values are written to the DIA (Device Information Area) at the time of manufacture.

That means a running program can calibrate itself by reading from the DIA. They can even be read from within the MPLAB X IDE or IPE, so a one-off design could use an accurate hard-coded value.

The DIA sits alongside the MUI and is read-only data imprinted on individual chip dies with a laser during device manufacture.

Since the comparator output is digital, it can be routed to any I/O pin or used internally to trigger interrupts. Separate rising and falling edge interrupts are also available. The comparator can even be used to trigger an ADC conversion.

CLC modules

The four CLC (Configurable Logic Cell) modules in the PIC16F18045 provide the option to implement either sequential or combinatorial logic. Each CLC module has four inputs and one output and can provide various fixed logic functions.

The CLC outputs can be directed to digital I/O pins or be used to trigger interrupts internally. The internally-generated CLC output can be used as one of the inputs to other (or the same) CLCs to allow more complex logic to be created. The intention is to avoid the need to add an extra external logic chip to achieve a specific function.

ADC advances

The ADC on the PIC16F180**15** and PIC16F180**45** is referred to as an 'ADCC' or analogue-to-digital converter with computation. The computation feature means that the hardware can do things like averaging or low-pass filtering and perform comparisons to trigger interrupts.

The ADCC also has hardware support for capacitive divider applications. A typical application for that is capacitive touch sensing. We experimented with this in the *ATtiny816 Breakout Board* using a standard ADC peripheral – see *PE*, July 2021.

The hardware support makes it simpler to implement touch sensing, while other features like the precharge control, guard ring and adjustable sampling capacitance make the sensing more robust.

12-bit differential ADC

On the PIC16F**18146** and PIC16F**17146**, there is also the benefit of a 12-bit (vs 10-bit) ADC and the option to perform differential readings between two channels. Note that while doing differential readings, both channels must sit inside the range set by the negative and positive ADC references.

A legacy mode makes it behave much the same as older parts, so just because there are new features doesn't mean that setting up the ADC is any more difficult.

Interestingly, the two PWM peripherals on the PIC16F18146 (with two 'slices' each, giving a total of four channels) do not require a separate timer to be configured, simplifying configuration in straightforward cases. The CCP peripheral can also be used to provide more PWM channels.

The PIC16F**18146** and PIC16F**17146** have the option of running the processor more slowly than the main clock. This is called 'DOZE mode', and the clock ratio can be set dynamically at runtime.

It's even possible to return the processor to full speed while interrupts are executing. That is handy for an application that needs to save power but also respond quickly to external events.

All these parts provide other peripherals for serial communication protocols such as SPI, UART and I^{2}C. We recommend taking a look at the data sheets (even just the contents) to get an idea of what else they provide.

Practical applications

We were curious about peripherals like the CLC and comparator, as we hadn't had much experience using these types of peripherals on a microcontroller. So, we thought we'd put them to the test and see what we

Table 3 – a comparison of the 20-pin PICs we tested

	PIC16F18045	PIC16F18146	PIC16F17146
Flash memory	14kiB	28kiB	28kiB
CPU Speed	8 MIPS	8 MIPS	8 MIPS
EEPROM	128 bytes	256 bytes	256 bytes
CCP channels	2	1	1
PWM channels	3 × 10-bit	2 × 16-bit	2 × 16-bit
8-bit timers	3	2	2
ADCs	1 × 17 channel	1 × 17 channel	1 × 17 channel
ADC resolution	10 bits	12 bits (differential)	12 bits (differential)
Comparators	1	2	2
Op amps	0	0	1
DAC	1 × 8-bit	2 × 8-bit	2 × 8-bit
Processor DOZE	No	Yes	Yes

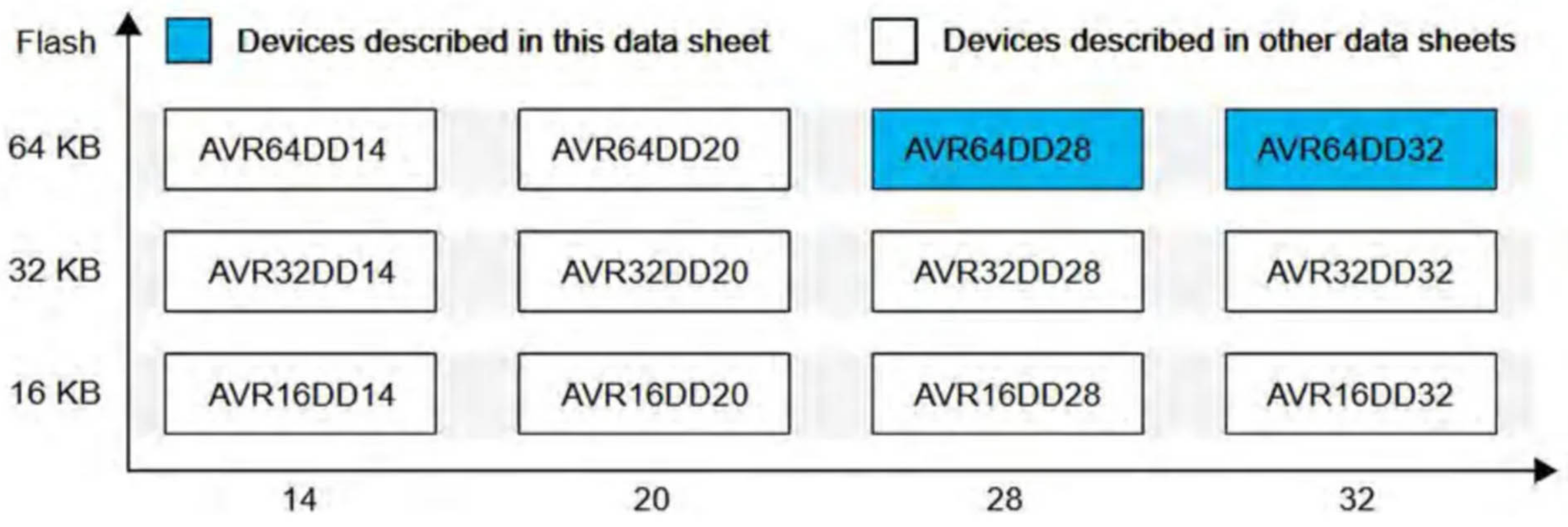


Fig.2: this excerpt from the AVR64DD32 data sheet shows the other members of the AVR DD family, with the AVR64DD32 being the most powerful. The other members have fewer Opins but still a similar number of peripherals.

could achieve with a minimum of external components.

We have designed a boost DC/DC converter using several of the chip's peripherals along with an inductor and low-side switch in the form of an N-channel MOSFET. This configuration also requires a diode and capacitor to capture the energy from the inductor.

We did some initial breadboard testing and succeeded in getting a circuit working with all four PICs we're looking at, including the tiny PIC16F18015.

It went so well that we have put together a demonstration board that does just that. We've secured some stock of the PIC16F18146, so we will base our PIC16F18146 Boost Regulator on this part. This project will be published in a future issue.

AVR64DD32

As we noted earlier, we have covered several AVR parts since the Microchip takeover of Atmel, and the AVR DD family is the latest. Like the earlier ATtiny816, AVR128D**A28** and AVR128D**A48** parts, the AVR64DD32 uses the single-wire UPDI programming interface.

UPDI stands for 'unified program and debug interface' and performs much the same role as ICSP (in-circuit serial programming) in PIC devices, although it is a pretty different protocol. It replaces the traditional SPI programming for AVRs that required more pins to be used.

The DD family appears to focus more on low pin count applications than the DA family. For example, the DD family data sheet shows parts from 14 to 32 pins, while the DA family has 28 to 64 pins.

Fig.2 is an excerpt from the AVR64DD32 data sheet and shows other members of the AVR DD family.

The DB family introduced MVIO (multi-voltage I/O), allowing some of the I/O pins to operate on a separate digital voltage domain, powered from a dedicated pin. The DD family also has the MVIO feature.

For the AVR64DD32, the four PORTC pins can use the MVIO feature, with a VDDIO2 pin controlling the second IO voltage. Whether MVIO is operational is set by a configuration fuse, so it cannot be changed at runtime.

There are status bits that report if the VDDIO2 rail is present and can trigger interrupts when it fails. If the VDDIO2 rail is too low, the MVIO pins are set to high impedance. The VDDIO2 rail can be between 1.8V and 5.5V, the same range as the main supply rail.

Like the AVR128DA, the AVR64DD32 has ample Flash memory and RAM. There are also 256 bytes of EEPROM. So it appears that the DD family has many of the features of the DA and DB families, but with smaller pin counts and package sizes.

CCL

CCL (Configurable Custom Logic) is a similar peripheral to the PIC CLC. It is also intended to provide simple logic that can be attached to the digital peripherals and eliminate the need for an external logic chip.

Rather than several fixed logic functions that can be selected (as for the PIC CLC), the CCL uses an eight-bit lookup table that takes three inputs and provides one output. It is an elegant idea and works well if you can reduce your logic to a truth table.

You can also add sequential elements such as flip-flops and latches to the logic. Like the PIC CLC, signals can be passed between CCL units to create more complex logic.

The AVR64DD32 also has peripherals that can provide serial communication features, as well as timers, a comparator, zero crossing detector and DAC. The ADC is a 12-bit differential type.

The AVR64DD32 does not have PPS, but most digital peripherals can be switched to one alternative pin. The pin allocation is quite good, with several peripherals able to be allocated to PORTC to make use of the MVIO feature, including groups such as, for example, the four lines needed to implement an SPI interface.

Software support

As we saw with the AVR128DA parts, the integration of AVR parts into MPLAB X is quite good. We had no trouble creating a simple project from scratch in MPLAB X v6.00 to flash one LED on a breadboard.

We encountered two minor problems with the AVR64DD32 and MPLAB X v6.00 but found solutions in online discussions. Those revealed that many people are interested in these new parts.

Since the PICkit 4 cannot provide power in UPDI mode, we resorted to using the Snap programmer modified to supply 5V power from its own USB supply. We explained how to do that in the *PIC Programming Helper* article from *PE*, June 2022.

The Snap has a pull-down on the pin used for UPDI, which interferes with programming. While we could have removed a resistor from the Snap, we found that a 1kΩ pull-up to the supply voltage (ie, between pins 2 and 4 on the Snap) was sufficient for UPDI programming to work.

Also, it appears that the button for

MICROCHIP
AVR64DD32

The AVR64DD32 is a Microchip / Atmel microcontroller with an AVR CPU core running at up to 24MHz. It is shown here in a VQFN-32 package but is also available in TQFP.

reading from the device in the Configuration Bits window of MPLAB X does not work. The workaround is simply to use the Read Device Memory button from the main toolbar instead.

The debugging feature works well. We could set breakpoints, pause program operation, view variables and view special function registers.

The default configuration fuse settings mean that the processor uses an internal 4MHz oscillator when it starts up; it can be changed at runtime to 24MHz with a line of code.

There are also options for using an external crystal or an internal or external 32.768kHz clock source. There is even the option of using a 48MHz clock (derived from a PLL) to feed peripherals that can use a higher clock speed than the processor (great for high-precision PWM).

With a lot of oscillator configuration able to be done in software, there is no longer the need or risk of setting the fuses to use an external oscillator, which could prevent reprogramming – an AVR bugbear. As with our ATtiny816 project, it wasn't necessary to change from the default configuration fuse settings, avoiding such problems.

Arduino compatibility

Since the Arduino ecosystem started with 8-bit AVR parts like the ATmega328, it is no surprise that a cohort continues to add support for newer Atmel parts to the Arduino IDE.

The core at: **https://bit.ly/3OEEJdI** supports many AVR Dx parts, including the promise of adding support for the AVR DD parts such as the AVR64DD32.

We haven't had a chance to try out DxCore since support for the AVR DD is so new, but it might be another way to start working with the AVR DD and other AVR Dx parts. You can find detailed installation instructions on the Installation page of the GitHub repository (linked above).

For those familiar with the process, it's as simple as adding this: **https://bit.ly/pe-oct23-draz** to the Additional Board Manager URLs and then installing the board package via the Boards Manager.

Breakout boards

We made a few small breakout boards to help test these parts, mainly to simplify connections to a programmer while the parts were on a breadboard. They're not much more than a small PCB with some headers and a handful of passive components, but they proved so handy that we've decided to make them available from the *PE PCB Service*.

See overleaf for information about the breakout boards and the parts you'll need to assemble them.

Summary

We plan to keep the PIC16F18146 as our new 20-pin 8-bit PIC part of choice. Its core is similar to the recent PICs we have used, although the new DOZE feature could be pretty handy for low-power applications.

While many recent parts support runtime Flash memory writing, a separate EEPROM space (as found on all three of the 20-pin PICs, and as described here) helps simplify development through its simpler interface and the ability to write a byte at a time.

Choosing a set of peripherals to match a project design and potentially unknown future applications can be tricky, but the PIC16F1814**6** has a good set for just a little more cost than the less capable PIC16F1804**5**.

That said, all three chips have a rich set of features, sufficient to fully implement the digital boost regulator which we used to demonstrate their capabilities. It's reassuring and handy to see this ability to drop in parts across families, especially when some parts remain in short supply.

Working with AVR parts in MPLAB X is now quite simple. If you're accustomed to working with PICs under MPLAB X and want to try AVR parts, try putting an AVR64DD32 onto one of our smaller breakout boards.

We look forward to the 14-pin and 20-pin members of the AVR64DD32 family becoming available. The AVR64DD32 data sheet indicates that some of these will have up to 64kiB of Flash memory and 8kiB of RAM.

With the AVR parts having a hardware multiplier that the PICs do not, and often much more Flash memory and RAM, we can see these parts becoming useful in more complex applications or those requiring substantial calculation and computation.

At the time of writing, Digi-Key (**www.digikey.com**), Mouser (**https://mouser.com**) and Microchip Direct (**www.microchipdirect.com**) all have stock of at least some of the PIC16F17146 and PIC16F18xxx chips. Stock of the AVR64DD32 is due in soon (October – December 2023).

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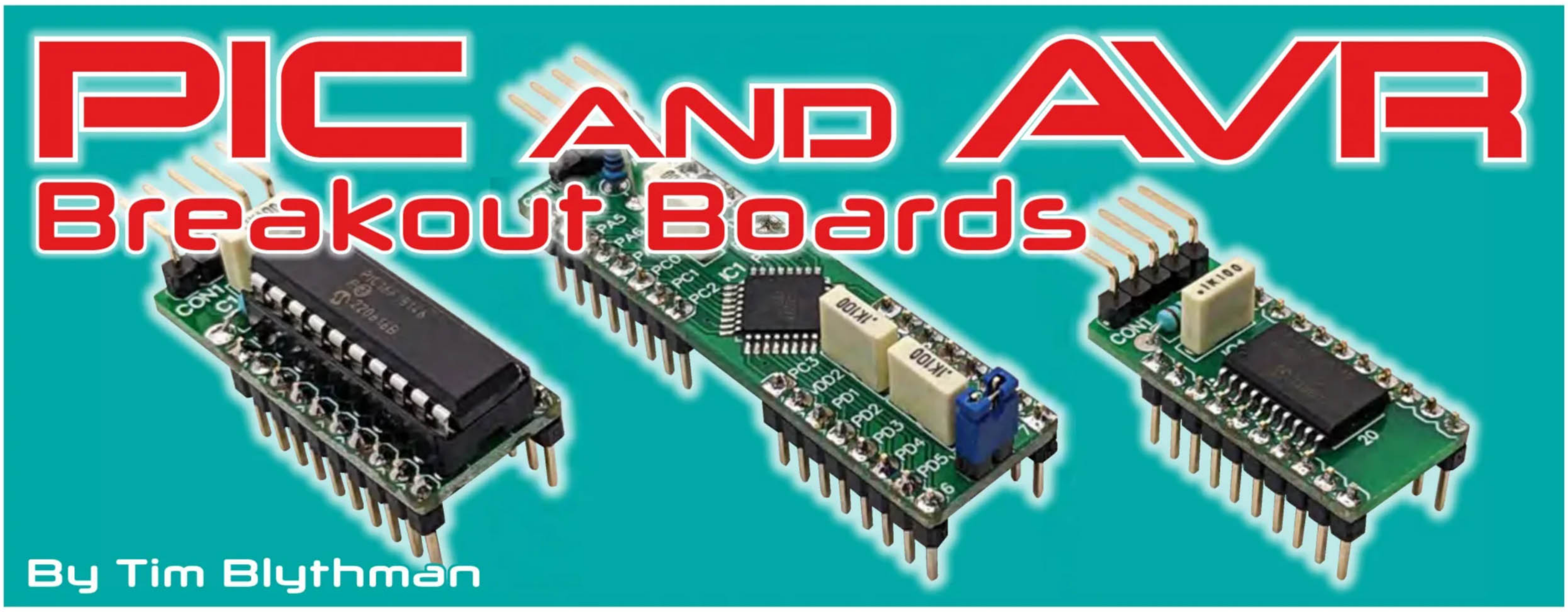

CON1
IC1
PA5
PA6
PC0
PC1
PC2
PC3
VDD2
PD1
PD2
PD3
PD4
PD5
.1K100
20

PIC AND AVR Breakout Boards

By Tim Blythman

The three Breakout Boards we designed are intended to plug into a breadboard while also connecting to a Snap or PICkit 4 programmer for power and programming.

Two can be used with the four PIC parts we discussed in the feature article: one for SOIC parts and the other for DIP. The circuit for these two boards is identical – see Fig.3.

The other is designed for the AVR64DD32 and its circuit is shown in Fig.6. The PICkit 4 cannot provide power in UPDI mode (as for newer AVR chips), so we recommend using a Snap modified to provide 5V with the AVR64DD32.

PIC Breakout

These *PIC Breakout Boards* accept SOIC (Fig.4) or DIP (Fig.5) devices up to 20 pins. They are designed to provide basic programmer connections as well as the two passive components needed for a minimal working setup.

They break out each pin of the microcontroller to an adjacent header pin. This could be a standard header below to plug into a breadboard, or a header socket above, into which you can plug jumper wires. We'll describe the parts needed to plug into a breadboard.

Many recent 8-bit PIC parts have standard pinouts on their topmost pins, shown as pins 1-4 and 17-20 in Fig.1. So this Breakout should work for most recent 8-pin, 14-pin and 20-pin 8-bit PICs, as long as they are placed at the top of the Breakout.

You could fit the DIP breakout with a 20-pin narrow IC socket to allow parts to be changed in and out. Alternatively, a narrow ZIF (zero insertion force) socket could be used, turning the *Breakout Board* into a handy programming jig.

Assembly of the PIC Breakout

During construction, refer to the appropriate overlay diagram, Fig.4 or Fig.5. Both are double-sided boards, with the SOIC version being 15.5 × 32.5mm and the DIP version being 15 × 35.5mm.

If you have the SMD version, start by soldering the microcontroller in place. If it is a 20-pin part, it will be a tight fit, so keep it clear of the pads for the header pins.

Apply flux and rest the chip in place, ensuring that pin 1 goes to the end near CON1. 8-pin and 14-pin parts won't be as fussy as they are narrower but should have their pin 1 in the same location.

Tack one lead and check that all the remaining pins are aligned before soldering the others. Check there are no bridges between pins or to the header pin pads; if there are, clean them up with flux, solder braid and a clean iron. Then use an appropriate solvent to remove any remaining flux.

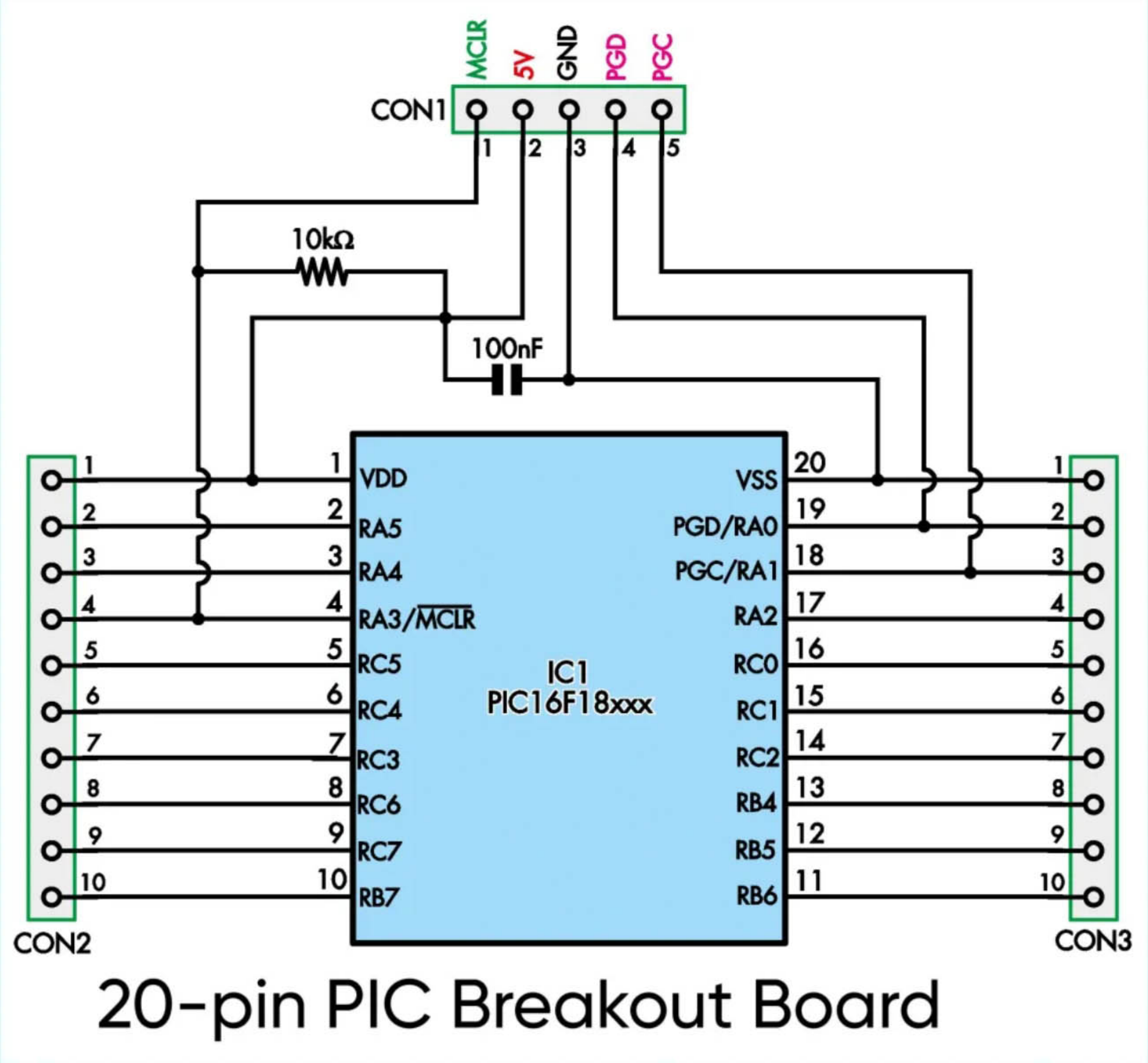
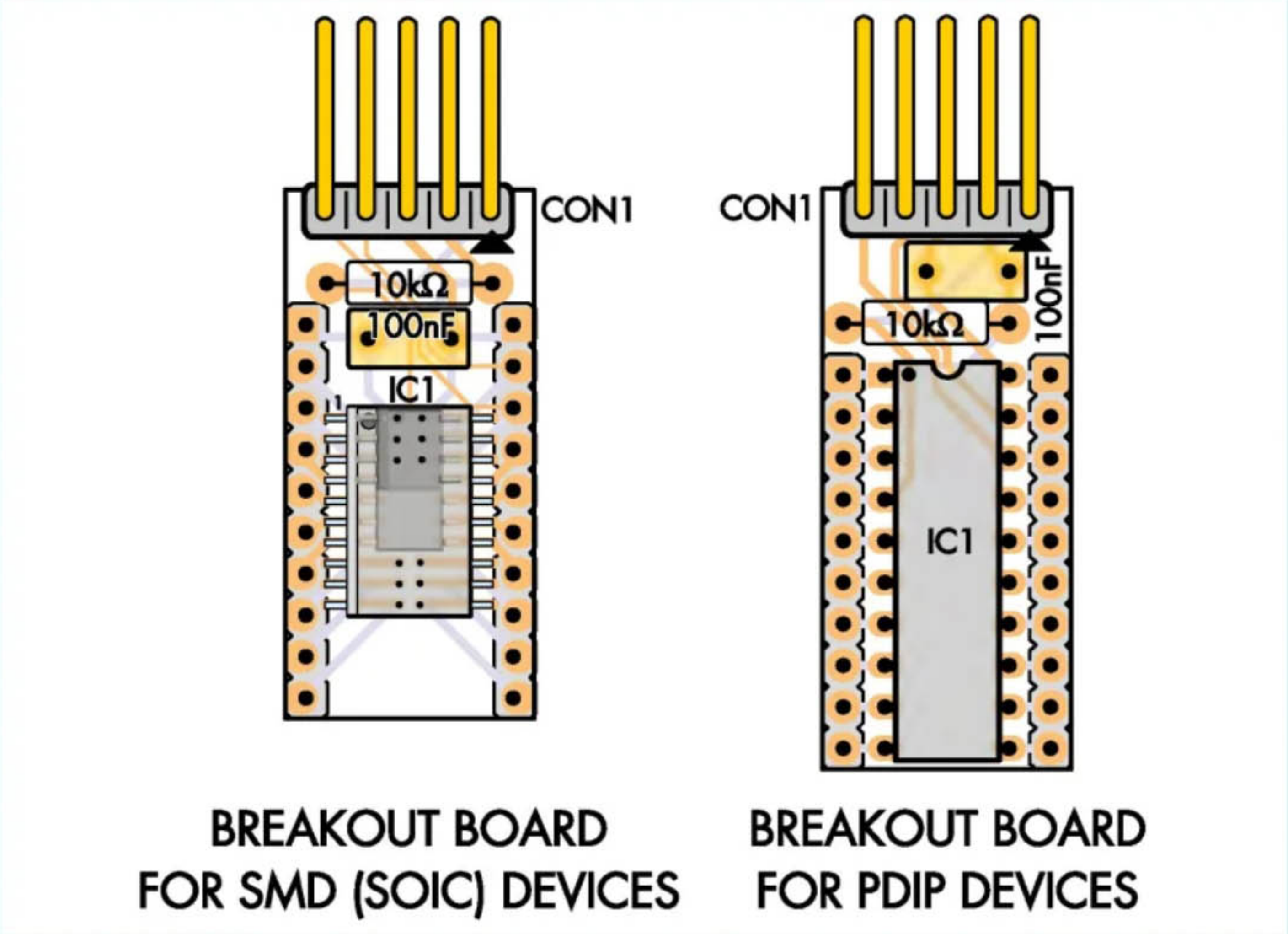

MCLR
5V
GND
PGD
PGC
CON1
1
2
3
4
5
10kΩ
100nF
IC1
PIC16F18xxx
VDD
RA5
RA4
RA3/MCLR
RC5
RC4
RC3
RC6
RC7
RB7
VSS
PGD/RA0
PGC/RA1
RA2
RC0
RC1
RC2
RB4
RB5
RB6
1
2
3
4
5
6
7
8
9
10
20
19
18
17
16
15
14
13
12
11
CON2
CON3
20-pin PIC Breakout Board

Fig.3: the 20-pin Breakout Board circuit connects the programmer header (CON1) to the chip with all pins also going to a pair of SIL headers.


CON1
10kΩ
100nF
IC1
CON1
10kΩ
100nF
IC1

BREAKOUT BOARD FOR SMD (SOIC) DEVICES

BREAKOUT BOARD FOR PDIP DEVICES

Figs.4 and 5: the breakout boards have been designed for breadboarding or general use (eg, plugging into a pair of SIL sockets). They accept 8, 14 and 20-pin devices with pin 1 in the same position.

If you have the DIP version, solder the socket or IC in place. Like the SMD part, you can tack one lead and then check that the socket or IC is flat and flush before soldering the other leads.

Next, solder the capacitor and resistor and trim their leads close to the PCB.

To fit and align the header pins, it's a good idea to plug them into a breadboard first. This will guarantee that the pins will align with the breadboard in the future. Place the PCB over the pins and push it down flat. Tack the corner pins and adjust if necessary before soldering the remaining pins.

Finally, fit the right-angled header, CON1. Then connect your programmer, being sure to align the arrows that mark pin 1 on both the programmer and the Breakout's programming header.

Parts List – PIC Breakout Board

1 double-sided PCB coded 24110225, 15.5 × 32.5mm (for SOIC parts) ***OR***
1 double-sided PCB coded 24110222 15 × 35.5mm (for DIP parts)
1 8/14/20 pin PIC16F18xxx microcontroller in SOIC/DIP package
1 20-pin DIL IC socket (**optional**; for DIP micros)
2 10-way pin headers, 2.54mm pitch
1 5-way right-angle pin header, 2.54mm pitch (CON1)
1 100nF MKT or ceramic capacitor
1 10kΩ axial ¼W resistor

All PCBs available from the PE PCB Service

Parts List – AVR64DD32 Breakout board

1 double-sided PCB coded 24110223, 16 × 53.5mm
4 8-pin headers, 2.54mm pitch
1 4-way right-angle male header, 2.54mm pitch (CON1)
1 2-way header and jumper shunt, 2.54mm pitch (JP1)
3 100nF MKT or ceramic capacitors
1 1kΩ axial ¼W resistor
1 AVR64DD32-I/PT 8-bit microcontroller, TQFP-32 (7×7mm) (IC1)

AVR Breakout

The PCB overlay for the 16 × 53.5mm AVR Breakout Board is coded 24110223 and is available from the PE PCB Service – it is shown in Fig.7. We've made it as narrow as possible to conserve breadboard space, resulting in a gap in the middle of the rows of pins. It therefore has 16 pins down each side, but they take up 20 rows on a breadboard.

Since there are two main power rails and the VDDIO2 pin for the MVIO feature, there are three bypass capacitors. The jumper shunt connects the two rails, which is necessary for applications that don't use MVIO.

The 1kΩ resistor on this board is connected between VDD and UPDI. This is discussed in the accompanying article and it is necessary if you are using a Snap programmer.

Assembling the AVR Breakout

The pitch of the TQFP AVR64DD32 chips is finer than SOIC parts, but still not too difficult to solder. Apply flux and rest the part roughly in place, ensuring pin 1 is in the correct location, then tack one lead. Take care to check that all four sides are aligned before tacking another pin on an opposite corner, then soldering all the remaining leads.

Remember that you can use flux, solder wicking braid and a clean iron to remove any bridges.

Fit the three capacitors next and follow with the 1kΩ resistor if that is needed. JP1 can be installed next. You should leave the jumper shunt in place unless you plan to connect an alternative VDDIO2 supply and activate MVIO.

Like the DIP PIC Breakout, you can align the header pins by pushing them into a breadboard first. Leave a gap of four rows in the middle, then push the PCB down firmly before soldering the pins.

Finally, fit the four-way header (CON1) for the programmer and attach the programmer. The arrow marks pin 1 and the programmer should have a corresponding mark.

MPLAB X

If you haven't used the MPLAB X IDE before, see our *PIC n' Mix* feature (*PE*, July and September 2020; January, March, May, July 2021). If you need to manually install the DFP (device family pack) for the AVR64DD32 or any of the PIC parts, use the Tools → Packs menu item.

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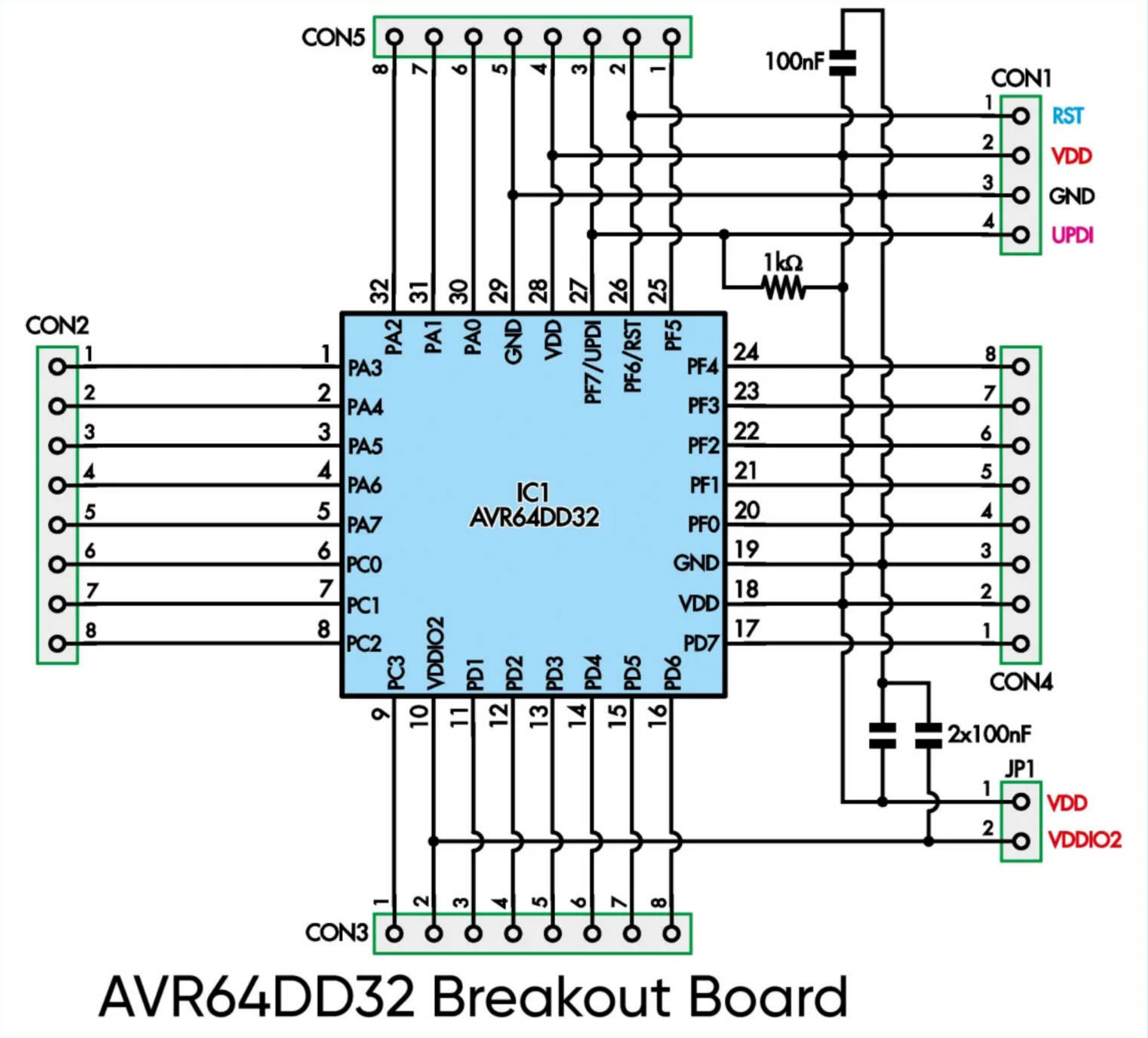

CON5
8
7
6
5
4
3
2
1
100nF
CON1
1 RST
2 VDD
3 GND
4 UPDI
1kΩ
32 31 30 29 28 27 26 25
PA2 PA1 PA0 GND VDD PF7/UPDI PF6/RST PF5
CON2
1 PA3
2 PA4
3 PA5
4 PA6
5 PA7
6 PC0
7 PC1
8 PC2
IC1
AVR64DD32
24 PF4
23 PF3
22 PF2
21 PF1
20 PF0
19 GND
18 VDD
17 PD7
PC3 VDDIO2 PD1 PD2 PD3 PD4 PD5 PD6
9 10 11 12 13 14 15 16
CON4
2x100nF
JP1
1 VDD
2 VDDIO2
CON3
AVR64DD32 Breakout Board

Fig.6: The AVR64DD32 Breakout Board is similar but brings the pins out to four headers as the chip has pins on four sides.

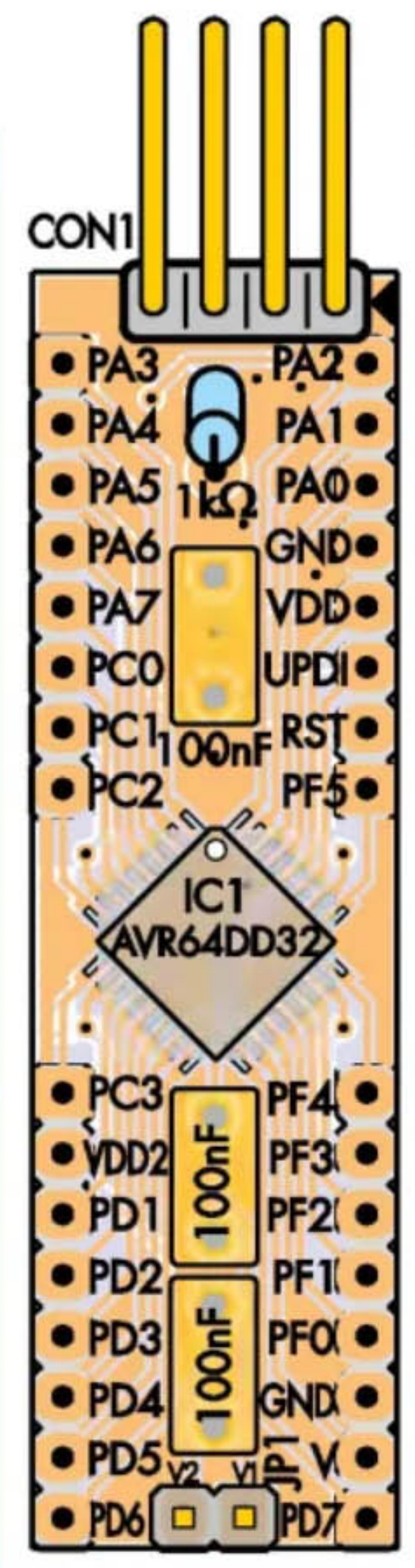

CON1
PA3
PA2
PA4
PA1
PA5
1kΩ
PA0
PA6
GND
PA7
VDD
PC0
UPDI
PC1
100nF
RST
PC2
PF5
IC1
AVR64DD32
PC3
PF4
VDD2
PF3
PD1
100nF
PF2
PD2
PF1
PD3
PF0
PD4
GND
PD5
100nF
V
PD6
V2
V1
JP1
PD7

Fig.7: the four headers are arranged in two rows so they can be plugged into a breadboard. The gaps mean the board is narrow enough for a standard breadboard.

Max's Cool Beans

By Max the Magnificent

Arduino Bootcamp – Part 10

If my retirement plan ever comes to fruition (a.k.a. winning the lottery), one of the first things I'm going to do is build myself a decent workshop. A few years ago, my chum Joe Farr, who lives in a little village outside London, created an air-conditioned construction attached to his house. When we are having a Zoom video call and Joe is showing me something running on the testbench, I can see his workspace with oscilloscope and logic analyser, soldering station, giant magnifying glass attached to his desk, and sundry other tools, all neatly arranged with lots of free space.

Spools of wire of every gauge and colour you can imagine are mounted on the wall to the side of Joe's desk, so all he needs to do is reach out, pull the required length, and snip it off. Another wall is covered floor-to-ceiling with little drawers packed with components beyond imagination. Most of the time, Joe can whip up a prototype of something we've been discussing using parts he already has to hand.

As I pen these words, by comparison, I'm sitting hunched over the keyboard at my dining room table, which is buried under a mountain of breadboards, flying wires, microcontrollers, components and tools. If I put anything down on the table in front of me and turn my head, then when I look back just a second later… it's gone. It's like magic.

All I can say is that as soon as I finish writing this column, my wife (Gina the Gorgeous) and I are going to hop in the car to go splash the cash on our weekly lottery ticket, thereby keeping the retirement dream alive.

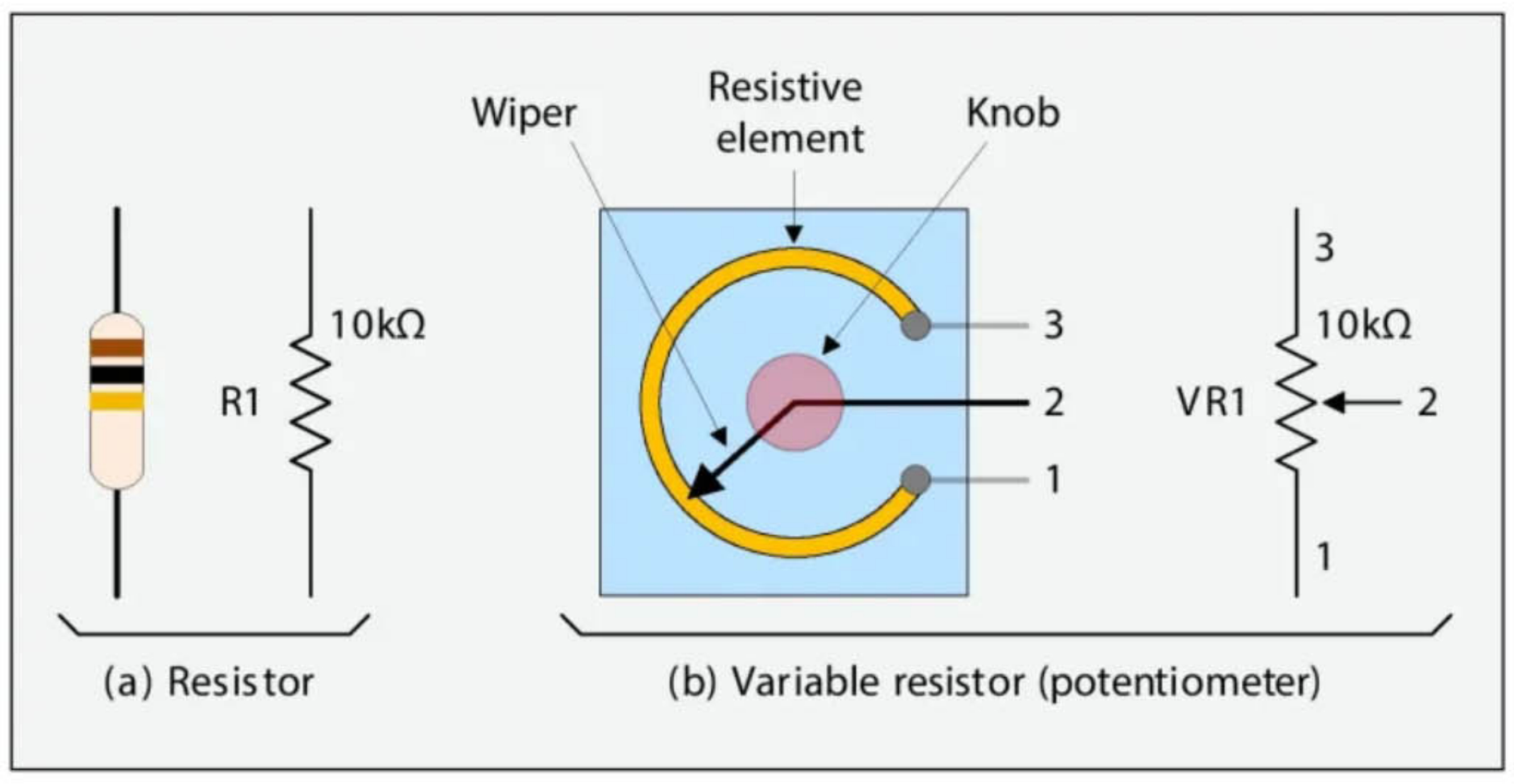


Fig.1. Graphical and symbol representations of fixed and variable resistors.

The knob on your side

Older readers may remember *The Goon Show*, which was a British radio comedy program that was originally produced and broadcast by the BBC Home Service from 1951 to 1960 (it was a big favorite of King Charles III, as I recall).

You can purchase a selection of scripts from **amazon.co.uk** if you wish (just search for 'Goon Show Scripts'). I have them on the shelves in my office. I'm thinking of the episode in which one of the characters is trapped in a basement. Another character says, 'Turn the knob on your side.' The first guy responds, 'I haven't got a knob on my side,' to which the second retorts, 'Of the DOOR, you idiot!' OK, you had to be there. But, speaking of knobs…

It varies

Thus far in this series of *Arduino Bootcamp* columns, we've used resistors with fixed values (Fig.1a). What we are going to do now is employ a variable resistor (Fig.1b). The way these little scamps usually work is by turning a knob (did you see what I just did there?) that slides a movable contact called the 'wiper' over a resistive element.

The value associated with a variable resistor (10kΩ in this example) refers to the total resistance between one end of the resistive element and the other (between pins 1 and 3 in this example).

Although variable resistors are conceptually simple, there are – as usual – a lot of fiddly details lurking 'under the hood' (or 'under the bonnet' in the English vernacular). First and foremost is the fact that there are three fundamental types of potentiometers, which are called linear (lin), logarithmic (log), and inverse logarithmic or anti-logarithmic (anti-log). Known as the resistance 'taper' (or 'curve' or 'law'), this refers to the relationship between the position of the wiper and the value of the resistive element (Fig.2).

The most common type is a linear taper in which the resistance varies in a linear fashion (in equal steps) in concert with the wiper position. In the case of a logarithmic taper, the resistance varies logarithmically (in progressively larger steps) with the position of the wiper. The response of the human ear to the loudness of sound is logarithmic, thereby allowing us to hear both very quiet and very loud sounds. This explains why one common use of variable resistors with logarithmic tapers is to act as volume controls in audio equipment; also, why the logarithmic taper is known by some as the 'audio taper.'

In rare cases, such as audio controls that are employed counterclockwise and in other specialised applications, anti-log versions are employed, so the anti-log taper may also be called the 'reverse audio taper.'

Variable resistors manufactured in Asia and the US are usually marked with an 'A', 'B', or 'C' for log, lin, and anti-log tapers, respectively.

Got potential?

One thing that often baffles beginners to electronics is that we sometimes use multiple terms for the same thing. As we've discussed in earlier columns, for example, a standard resistor may also be referred to as a pull-up resistor, a pull-down resistor, a current-limiting resistor, and so on. It's the same physical device type, but the qualification helps inform us what we are using it for.

Although we would never do so (unless we were desperate), we could employ a *variable* resistor as a fixed resistor if we so-desired (Fig.3a). When we refer to this device as a 'variable resistor', we

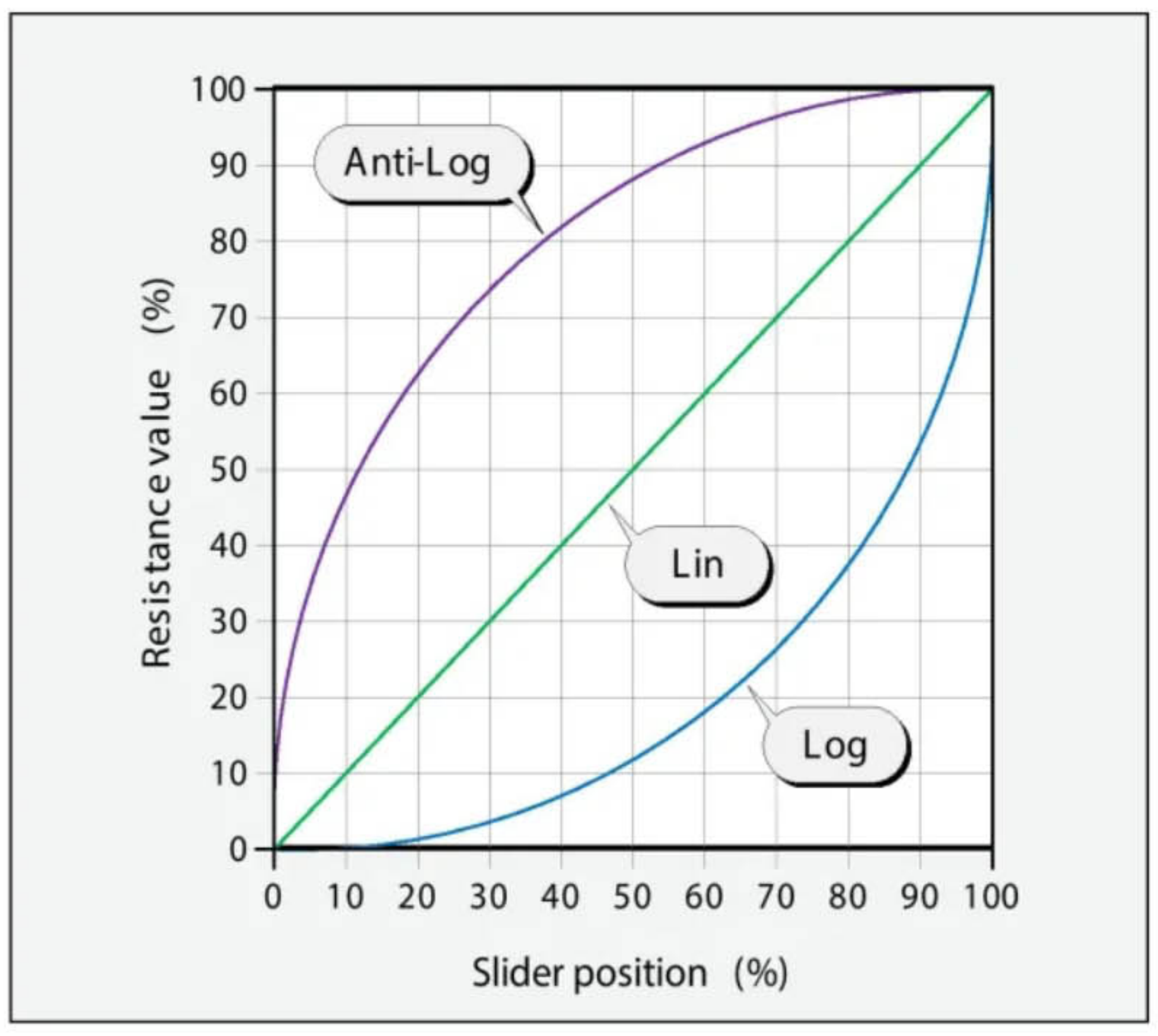
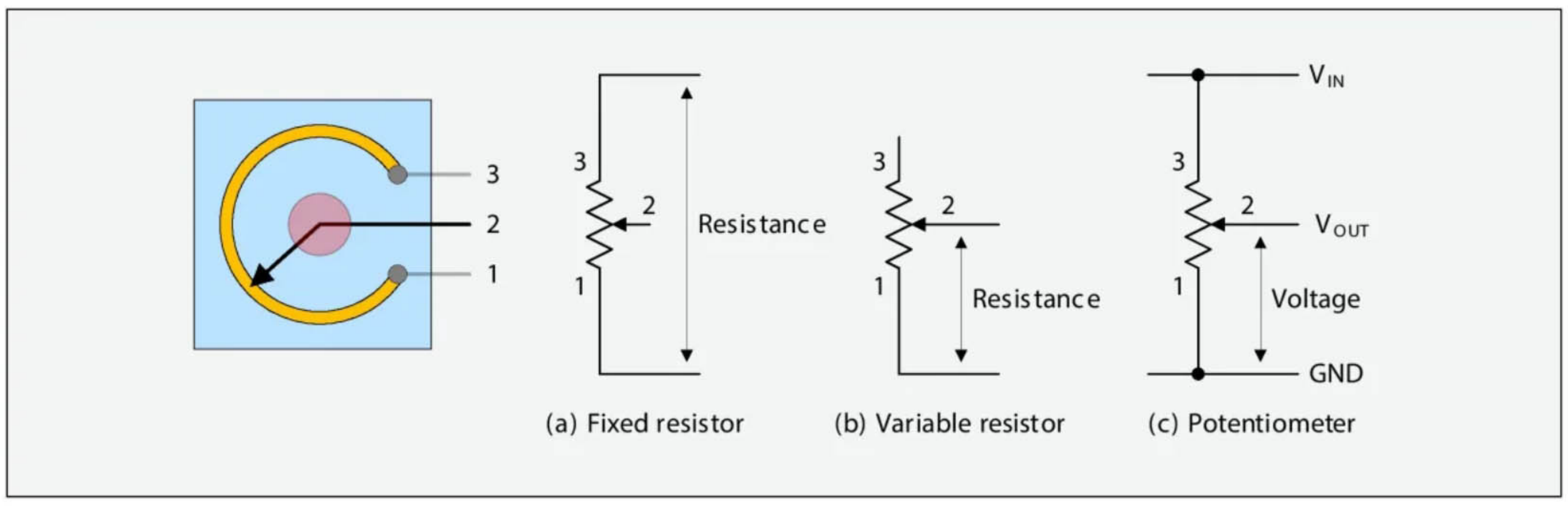


Fig.2. Different variable resistor tapers.



(a) Fixed resistor (b) Variable resistor (c) Potentiometer

Fig.3. Variable resistor or potentiometer?

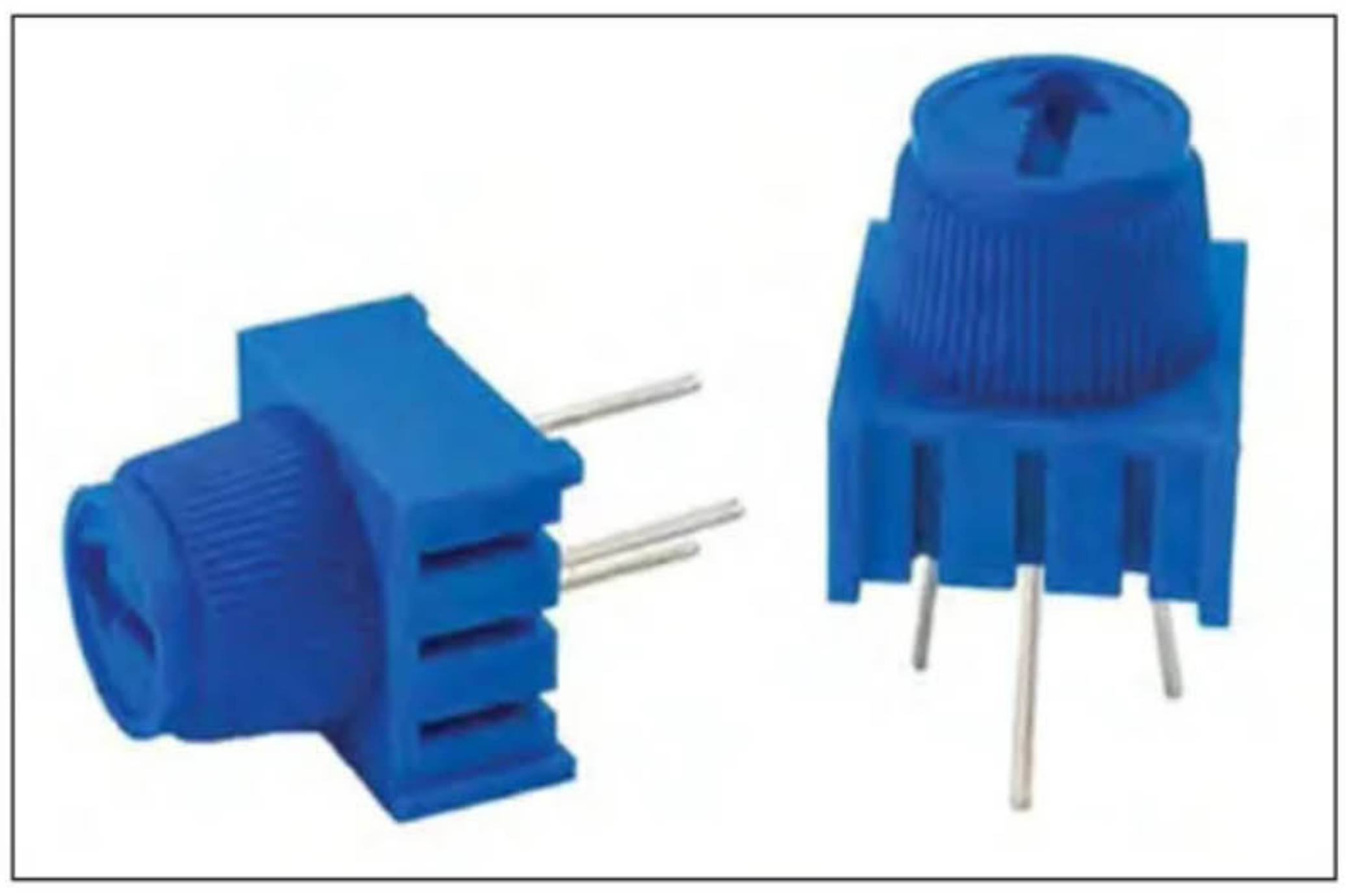


Fig.5. Breadboard-mounting trimpot.

are actually implying that we are using only two of its three terminals, one of which is connected to the wiper. Assuming the device is physically implemented as illustrated in our diagrams, and that we are using terminals 2 and 1 (Fig.3b), then rotating the knob clockwise will increase the resistance, while rotating the knob anticlockwise will decrease the resistance. Alternatively, if we were to use terminals 2 and 3, then the resistive response would be reversed.

Last, but certainly not least, when a variable resistor is employed as a potential divider by using all three terminals (Fig.3c), then we refer to it as a 'potentiometer', or just 'pot' for short.

Purely for the sake of interest, the potentiometer concept was first developed by the German physicist Johann Christian Poggendorff in 1841. The etymology of this word has its origin in 1868 as a hybrid formed from the combination of 'potentio,' derived from the Latin *potentia*, meaning 'power' (think potential), and 'meter,' from the Greek *metron*, meaning 'measure.' (I don't know about you, but I love knowing where words come from).

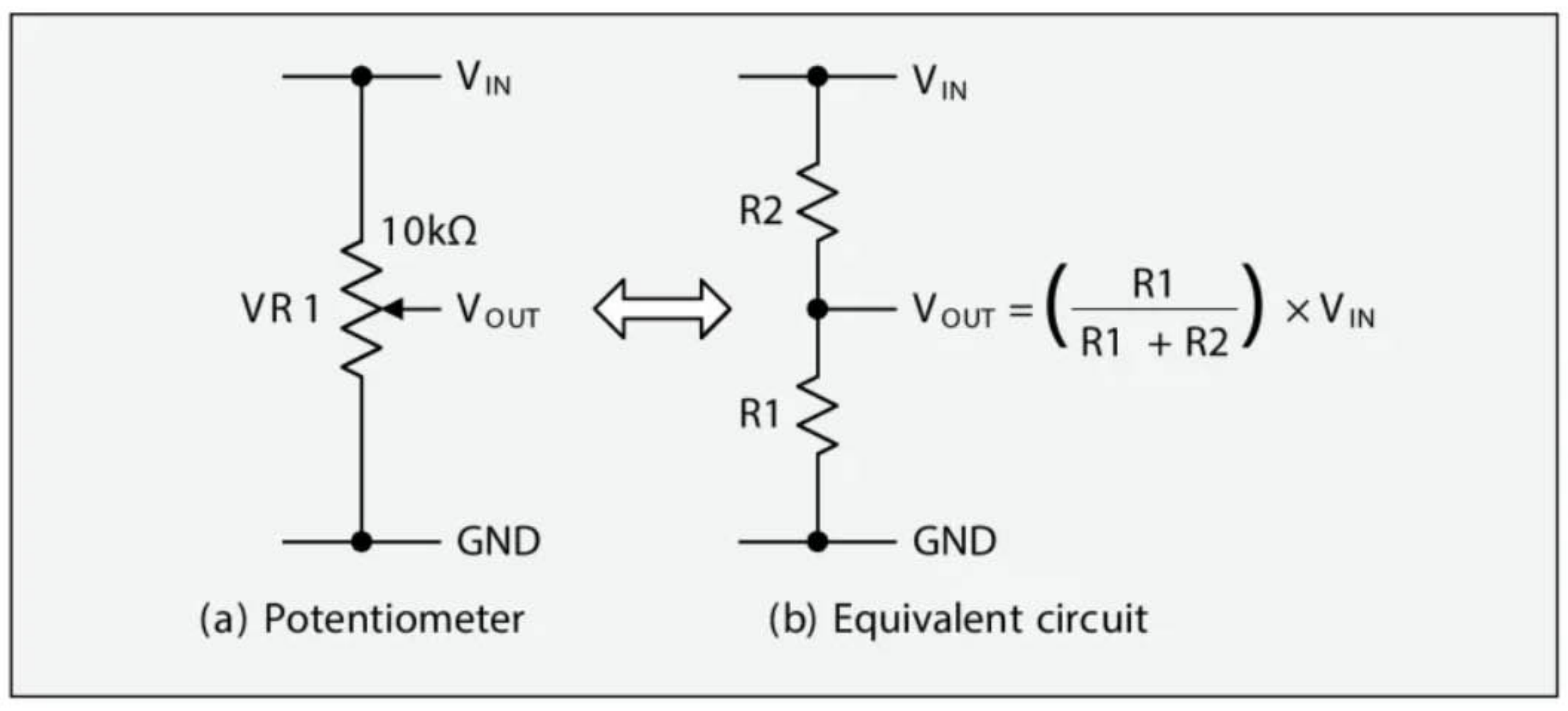
Mathematically speaking

On the one hand, you don't need to know what I'm about to tell you (at least, not for the purpose of our experiments here). On the other hand, I personally like to understand the nitty-gritty details of how things work.

Consider a variable resistor being used as a potentiometer (Fig.4a). We can visualise the wiper as being attached to a tap point between two resistors (Fig.4b). I'm sad to say I don't know the etymology of 'tap' in this context. However, I do know that it's a 'backronym' (ie, an acronym invented after the fact) for 'terminal access point' in the context of networking applications.

As we see, the output voltage (V_{OUT}) is calculated as the input voltage (V_{IN}) multiplied by (R1 / (R1 + R2)). If we assume that things are physically implemented as shown in our diagrams, and that the knob is rotated fully clockwise, then R1 will be 10kΩ and R2 will be 0Ω, which means (R1 / (R1 + R2)) will evaluate to 1, so $V_{OUT} = V_{IN}$. Contrariwise, if the knob is rotated fully anticlockwise, then R1 will be 0Ω and R2 will be 10kΩ, which means that (R1 / (R1 + R2)) will evaluate to 0, so $V_{OUT} = 0$.

Finally, suppose the wiper is in the middle, which means R1 and R2 will both be 5kΩ. In this case, (R1 / (R1 + R2)) will evaluate to 0.5, so V_{OUT} will be half of V_{IN}.



(a) Potentiometer (b) Equivalent circuit

Fig.4. Calculating the resistance.

You may be saying, 'Well, that's obvious,' to yourself, but everything is once you know how to do it. All I know is that I would have really appreciated someone explaining this stuff to me when I was first starting out.

Feeling trim?

The term 'trimmer potentiometer' or 'trimpot' refers to a small potentiometer that is used to adjust, finetune, and calibrate circuits. Whereas regular potentiometers are typically mounted on the front panel of a piece of electronic equipment, trimpots are usually mounted directly on the printed circuit board (PCB).

Generally speaking, the main difference between a pot and a trimpot is size and attachment location/mechanism. Having said this, many trimpots are created in such a way that they can only be adjusted by means of a small screwdriver or other tool.

For the purposes of our experiment, we will be using a trimpot suitable for mounting on a breadboard (Fig.5). I purchased a 10-pack from Amazon in the US (**https://bit.ly/3YErn5F**), which is where I currently hang my hat. A similar pack is available from Amazon in the UK (**https://bit.ly/3QAuz04**). For myself, I like to have a few spares standing by, but we will require only one of these little rascals for our experiments, so you might be able to track down a one-off for a little less lucre.

Say toodles to the trembler

I don't know about you, but my breadboard is becoming a tad crowded. I don't think we will be using the trembler (vibration) switch we introduced in our previous column (*PE*, September 2023) for a while, so I've removed that from my breadboard and replaced it with one of my trusty trimpots, as illustrated in Fig.6.

As usual, all of the files mentioned in this column are available from the October 2023 page of the *PE* website at: **https://bit.ly/pe-downloads**

And, also as usual, you can download an image of our current breadboard layout showing the switches, our new

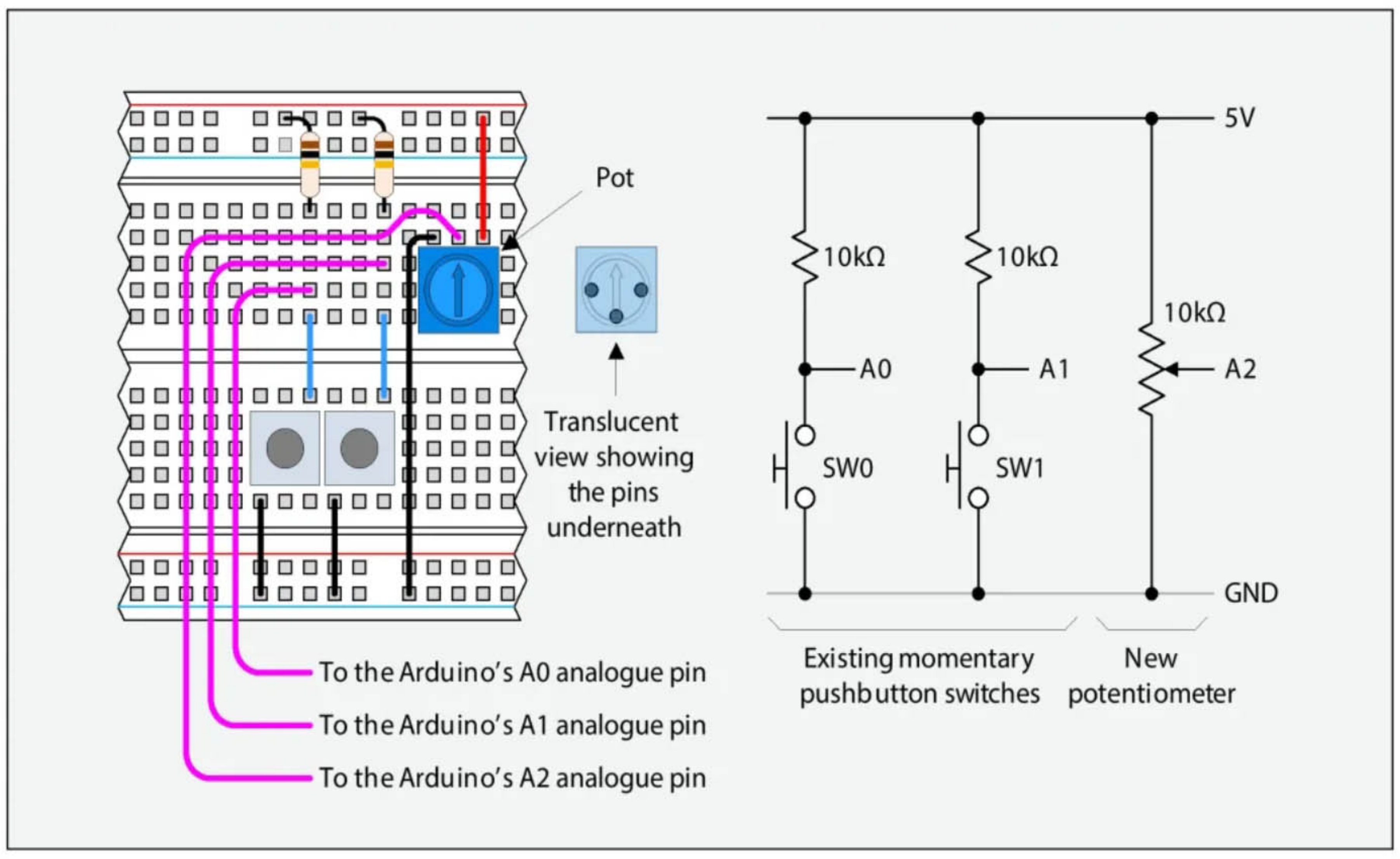
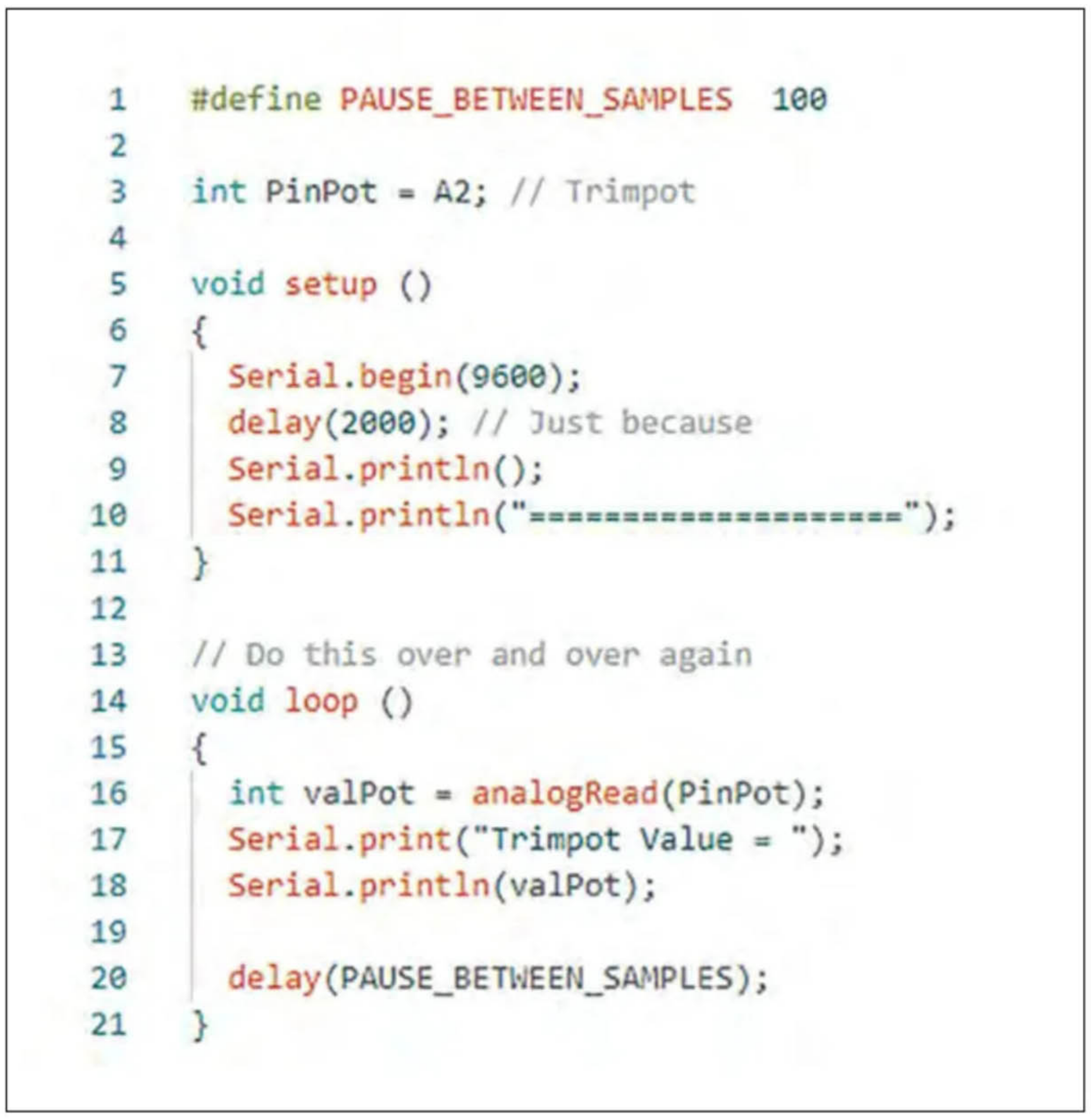

Pot
Translucent view showing the pins underneath
To the Arduino's A0 analogue pin
To the Arduino's A1 analogue pin
To the Arduino's A2 analogue pin
5V
10kΩ
10kΩ
10kΩ
A0
A1
A2
SW0
SW1
GND
Existing momentary pushbutton switches
New potentiometer

Fig.6. Adding the trimpot to the breadboard.



```
1   #define PAUSE_BETWEEN_SAMPLES  100
2
3   int PinPot = A2; // Trimpot
4
5   void setup ()
6   {
7     Serial.begin(9600);
8     delay(2000); // Just because
9     Serial.println();
10    Serial.println("====================");
11  }
12
13  // Do this over and over again
14  void loop ()
15  {
16    int valPot = analogRead(PinPot);
17    Serial.print("Trimpot Value = ");
18    Serial.println(valPot);
19
20    delay(PAUSE_BETWEEN_SAMPLES);
21  }
```

Listing 1. First-pass trimpot test.

trimpot, our buzzer, and our 7-segment display – along with various pull-up and current-limiting resistors – coupled with the connections to our Arduino Uno (file **CB-Oct23-01.pdf**).

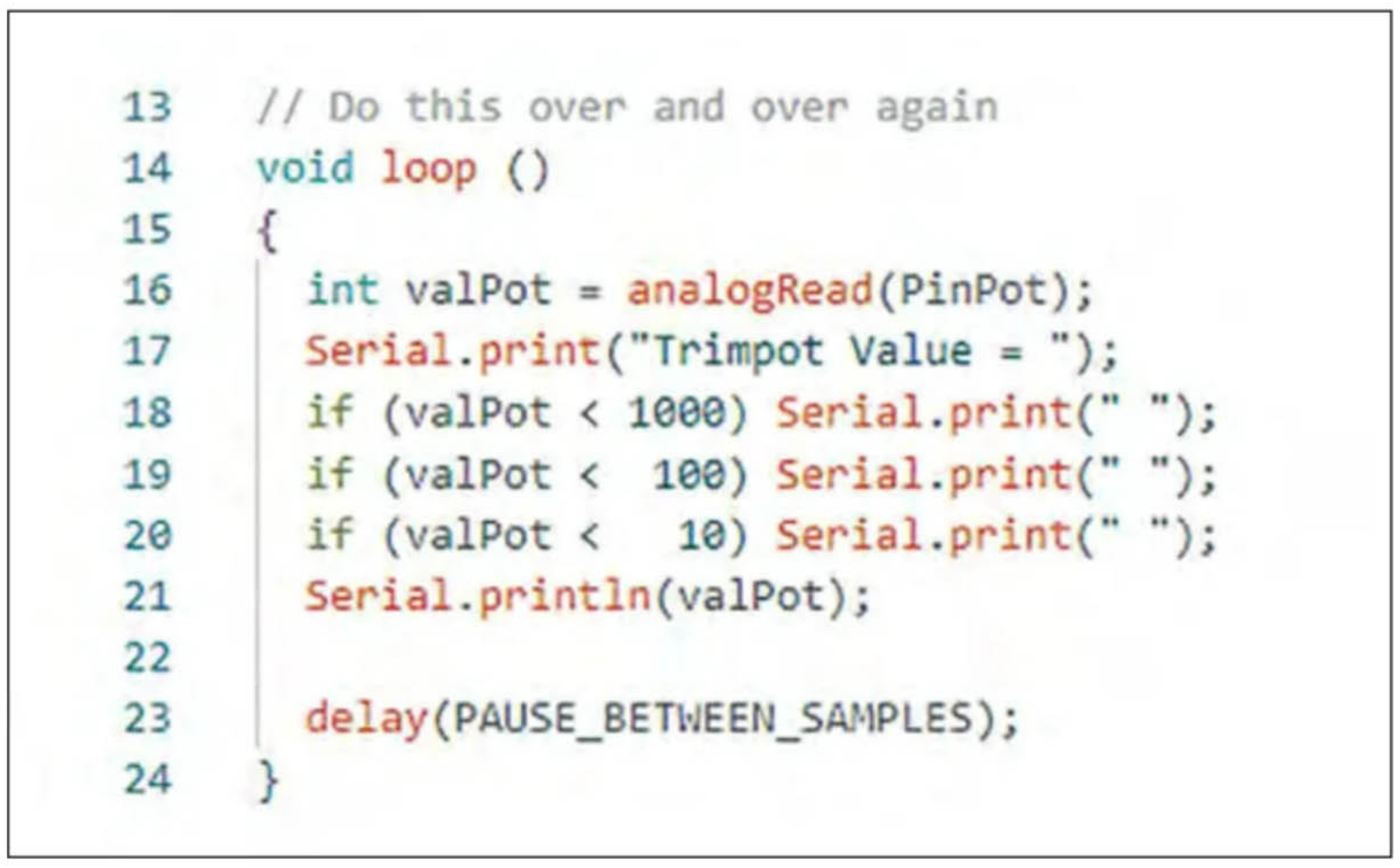
The trimpot translucent view is intended to represent what we would see if we were looking down on a semi-transparent trimpot so we can visualise how the pins should be oriented underneath. For the devices we are using, we can rotate them by hand or by means of a small screwdriver inserted into the 'arrow.'

The knob and shaft on our trimpot can only rotate through 270° (multiturn devices are available). With things as shown in Fig.6, the arrow is pointing at its halfway position. If we think of the arrow as being the hour hand on a clock, then when rotated fully anticlockwise or fully clockwise it will be pointing at approximately 7 o'clock and 5 o'clock, respectively.

Work, does it?

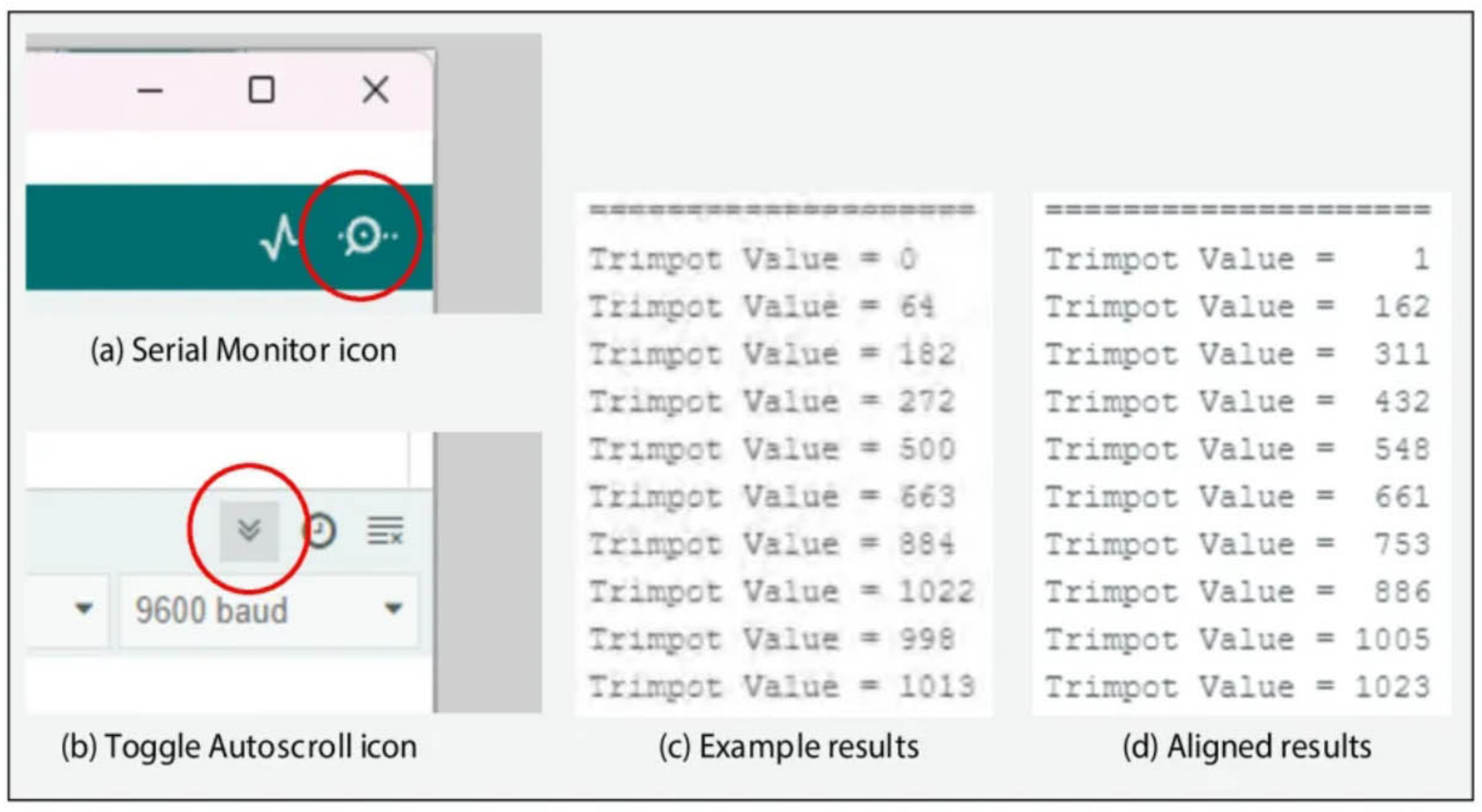
So, does our trimpot actually work? Let's see, shall we? Enter the program shown in Listing 1 (file **CB-Oct23-02.txt**). On Line 1 we define a delay of 100 milliseconds (1/10 second). On Line 3 we declare a variable called `PinPot`, to which we assign the Arduino's analogue input `A2` (this is the pin we connected to the signal from our trimpot as shown in Fig.6).

All we do in the `setup()` function is call `Serial.begin()` to activate the serial communications function, assign it the default speed of 9600 bits per second, and output a couple of lines of text to our Serial Monitor window.



```
13  // Do this over and over again
14  void loop ()
15  {
16    int valPot = analogRead(PinPot);
17    Serial.print("Trimpot Value = ");
18    if (valPot < 1000) Serial.print(" ");
19    if (valPot <  100) Serial.print(" ");
20    if (valPot <   10) Serial.print(" ");
21    Serial.println(valPot);
22
23    delay(PAUSE_BETWEEN_SAMPLES);
24  }
```

Listing 2. Just a little change.



(a) Serial Monitor icon

(b) Toggle Autoscroll icon

```
====================
Trimpot Value = 0
Trimpot Value = 64
Trimpot Value = 182
Trimpot Value = 272
Trimpot Value = 500
Trimpot Value = 663
Trimpot Value = 884
Trimpot Value = 1022
Trimpot Value = 998
Trimpot Value = 1013
```

(c) Example results

```
====================
Trimpot Value =    1
Trimpot Value =  162
Trimpot Value =  311
Trimpot Value =  432
Trimpot Value =  548
Trimpot Value =  661
Trimpot Value =  753
Trimpot Value =  886
Trimpot Value = 1005
Trimpot Value = 1023
```

(d) Aligned results

Fig.7. IDE icons and example results.

The `loop()` function is just as simple. On Line 16 we declare an `int` (integer) variable called `valPot` ('the value read from the potentiometer') to which we assign the value returned from the `analogRead()` function. On Line 17 we use a `Serial.print()` statement to output some text to the Serial Monitor window without throwing a new line. On Line 18 we use a `Serial.println()` statement to output the current value in `valPot` while also throwing a new line. Last, but certainly not least, on Line 20 we pause for breath before doing it all again.

Enter this program into your Arduino's integrated development environment (IDE) and upload it into your Arduino Uno. Once the upload is complete, activate the Serial Monitor by clicking the appropriate icon in the upper-right-hand corner of the IDE (Fig.7a).

After a couple of seconds, results will start to appear in the Serial Monitor (Fig.7c). Even though we set our `PAUSE_BETWEEN_SAMPLES` value to be 1/10 of a second, the values stream by at a high rate. One thing we can do is to click the Toggle Autoscroll icon in the upper-right-hand corner of the Serial Monitor window (Fig.7b). This stops the window scrolling, although new values continue to be appended to the bottom of the display. We can use the mouse to drag the scrollbar located at the right-hand side of the Serial Monitor window to wander back and forth through the results. Clicking the Toggle Autoscroll icon again will return the display to its automatic scrolling mode.

Another thing that we might opt to do is change our `PAUSE_BETWEEN_SAMPLES` value to be something like 2000 (two seconds), which will slow things down nicely.

Wait, what?

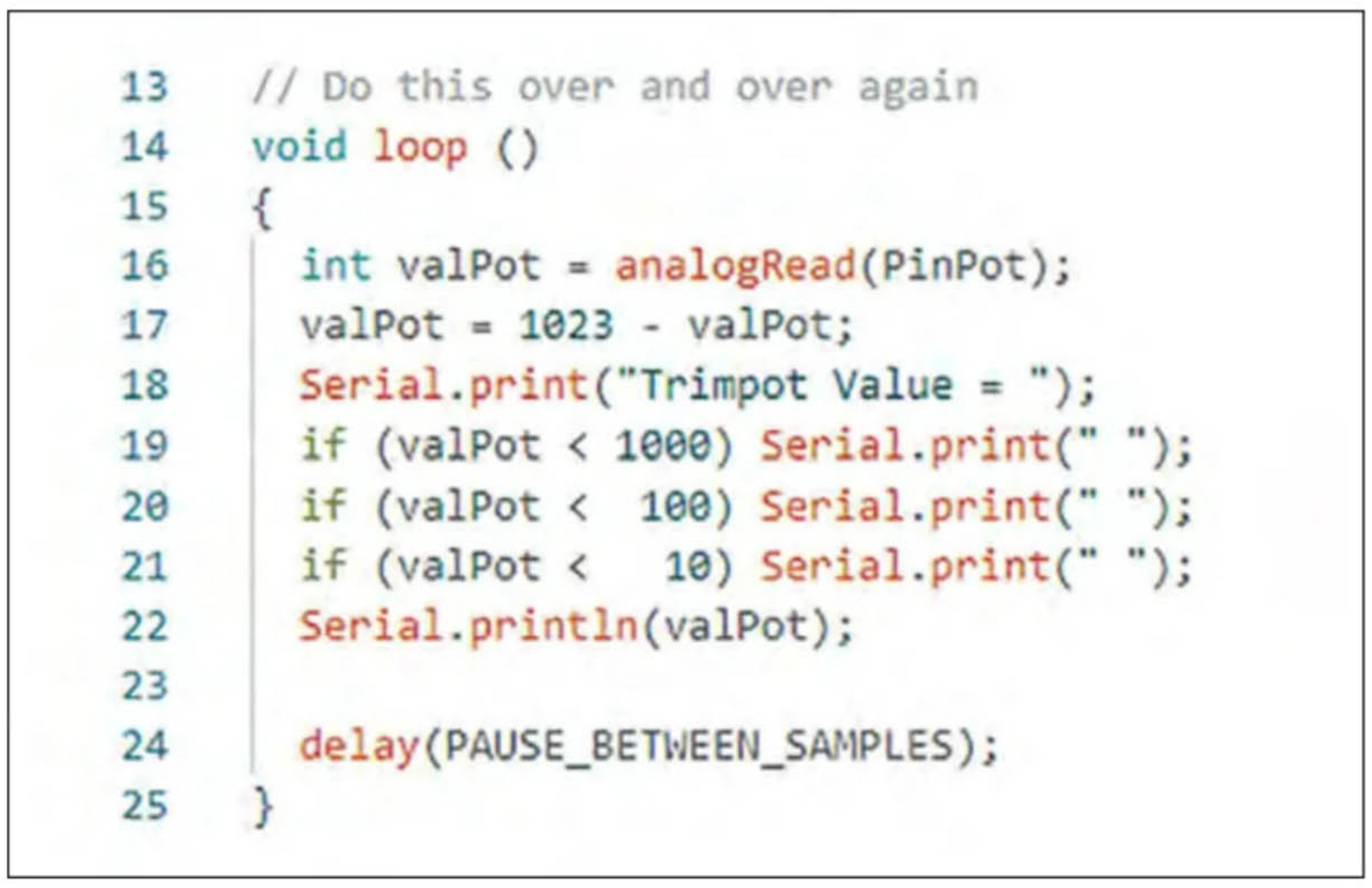
Take another look at the results that are appearing on your screen and the example results in Fig.7c. What do these numbers actually mean?

So, here's the deal. The Arduino Uno has a 10-bit analogue-to-digital converter (ADC). As we know, 10 bits can be used to represent $2^{10} = 1024$ different patterns of 0s and 1s, which we can use to represent unsigned (positive) integers in the range 0 to 1023.

When we call our `analogRead()` function to read the voltage from our trimpot, we know that voltage can theoretically range between 0V and 5V. The ADC presents this voltage range to us as integer values from 0 to 1023 (if your trimpot only returns values slightly higher than 0 and slightly lower that 1023, this just means the wiper can't quite reach the extents of its range).

Are we aligned?

Take yet one more look at the example results in Fig.7c. Is there anything about these results that irks you in any way? This raggedy presentation really gets my dander up. I prefer my numbers to be right aligned, especially when I have more than the single column we have here.



```
13  // Do this over and over again
14  void loop ()
15  {
16    int valPot = analogRead(PinPot);
17    valPot = 1023 - valPot;
18    Serial.print("Trimpot Value = ");
19    if (valPot < 1000) Serial.print(" ");
20    if (valPot <  100) Serial.print(" ");
21    if (valPot <   10) Serial.print(" ");
22    Serial.println(valPot);
23
24    delay(PAUSE_BETWEEN_SAMPLES);
25  }
```

Listing 3. Reversing the trimpot's action.

Let's modify our `loop()` function as shown in Listing 2 (file **CB-Oct23-03.txt**). The changes in question appear in Lines 18, 19 and 20. If the value in `valPot` is less than 1000, we print a space. Similarly, if the value is less than 100 and less than 10, we print additional spaces. The result is an alignment that would bring a tear of joy to a Regimental Sergeant Major's eye (Fig.7d).

It's 'Backwards Day'

To be honest with you, I was sort of surprised that things worked out the way they did – that is, rotating the trimpot's knob anticlockwise reduced the value being displayed, while rotating it clockwise increased the value being displayed. I don't know why, but most of the time I do this, it ends up that my pot works backwards (the opposite way) to what I intended.

Of course, it's possible we actually wanted the pot to work the other way round such that rotating the knob anticlockwise *increases* the output value, and so forth.

There are several ways to address this issue. We could fix it in hardware by swapping the power and ground connections to the trimpot. Alternatively, we could modify things in software by subtracting any values we read from the trimpot from 1023 as shown in Listing 3 (file **CB-Oct23-04.txt**).

As we see, this required the addition of only a single statement on Line 17. The result is to 'mirror' the values, so 1023 minus a trimpot reading of 0 returns 1023, while 1023 minus a trimpot reading of 1023 returns 0, and so on for any intermediate values. Try entering this new version of the program into your Arduino and verify that it works as planned.

Are you a convert?

Just for giggles and grins, let's say that, instead of displaying values in the range 0 to 1023, we wish to see these values represented as voltages between 0V and 5V rounded to the nearest volt.

One way to do this is to use the Arduino's built-in `map()` function, which re-maps a number from one range to another. This function requires five parameters: `value` (the variable to be processed), `fromLow`, `fromHigh`, `toLow` and `toHigh`. A value of `fromLow` gets mapped to `toLow`, a value of `fromHigh` to `toHigh`, and any values in-between to values in-between.

In addition to implementing this new functionality, let's also return to 'Forwards Day' by replacing the Line 17 we just added with our new `map()` statement, as illustrated in Listing 4 (file **CB-Oct23-05.txt**).

This really is a pretty clever function because the 'from' range can be larger than the 'to' range (the way we are using it), or the 'from' range can be smaller than the 'to' range, in which case the function will perform linear interpolations as required. Also, the 'low' values can be smaller than the 'high' values (the way we are using it), or one or both 'low' values can be larger than their corresponding 'high' values, in which case the function will return just what you would expect it to (assuming you expect what it returns, of course).

Components from Part 1

LEDs (assorted colours)	https://amzn.to/3E7VAQE
Resistors (assorted values)	https://amzn.to/3O4RvBt
Solderless breadboard	https://amzn.to/3O2L3e8
Multicore jumper wires (male-male)	https://amzn.to/3O4hnxk

Components from Part 2

7-segment display(s)	https://amzn.to/3Afm8yu

Components from Part 5

Momentary pushbutton switches	https://amzn.to/3Tk7Q87

Components from Part 6

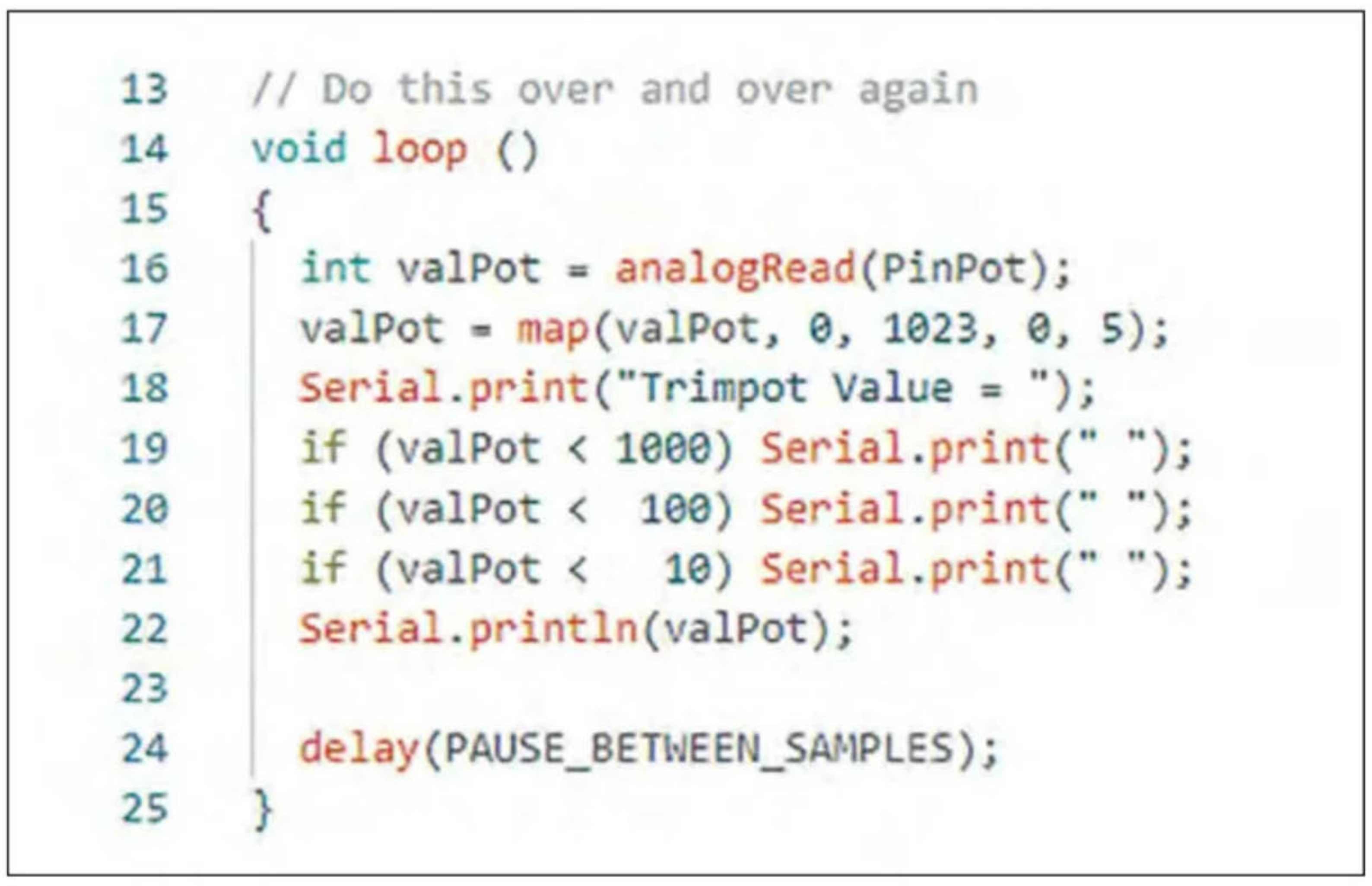
Passive piezoelectric buzzer	https://amzn.to/3KmxjcX

Components for Part 9

SW-18010P vibration switch	https://bit.ly/46SfDA4

Components for Part 10

Breadboard mounting trimpots	https://bit.ly/3QAuz04



```
13  // Do this over and over again
14  void loop ()
15  {
16    int valPot = analogRead(PinPot);
17    valPot = map(valPot, 0, 1023, 0, 5);
18    Serial.print("Trimpot Value = ");
19    if (valPot < 1000) Serial.print(" ");
20    if (valPot <  100) Serial.print(" ");
21    if (valPot <   10) Serial.print(" ");
22    Serial.println(valPot);
23
24    delay(PAUSE_BETWEEN_SAMPLES);
25  }
```

Listing 4. Mapping between number ranges.

Time for homework

Several potential tasks for you to play with popped into my mind while I was writing this column. Perhaps you could work on these to see how well you do, and we'll compare results when next we meet:

1. Modify our latest program so it displays voltage values with two significant fractional digits, such as 0.00, 1.41, 3.30, 4.99, and 5.00.
2. Modify the program such that it only displays a new value in the Serial Monitor if the voltage changes by 0.01V or more.
3. Map the 0 to 1023 input values onto a range of 0 to 9 and, in addition to writing these values to the Serial Monitor, present them on our 7-segment display.
4. Augment the previous program to also cause our piezo-electric buzzer to play one of ten musical notes, with 0 corresponding to middle C (that's C_4 in scientific pitch notation).

That should keep you busy for a while. Feel free to email me to tell me how you are getting on. Until next time, have a good one!

Cool bean Max Maxfield (Hawaiian shirt, on the right) is emperor of all he surveys at **CliveMaxfield.com** – the go-to site for the latest and greatest in technological geekdom.

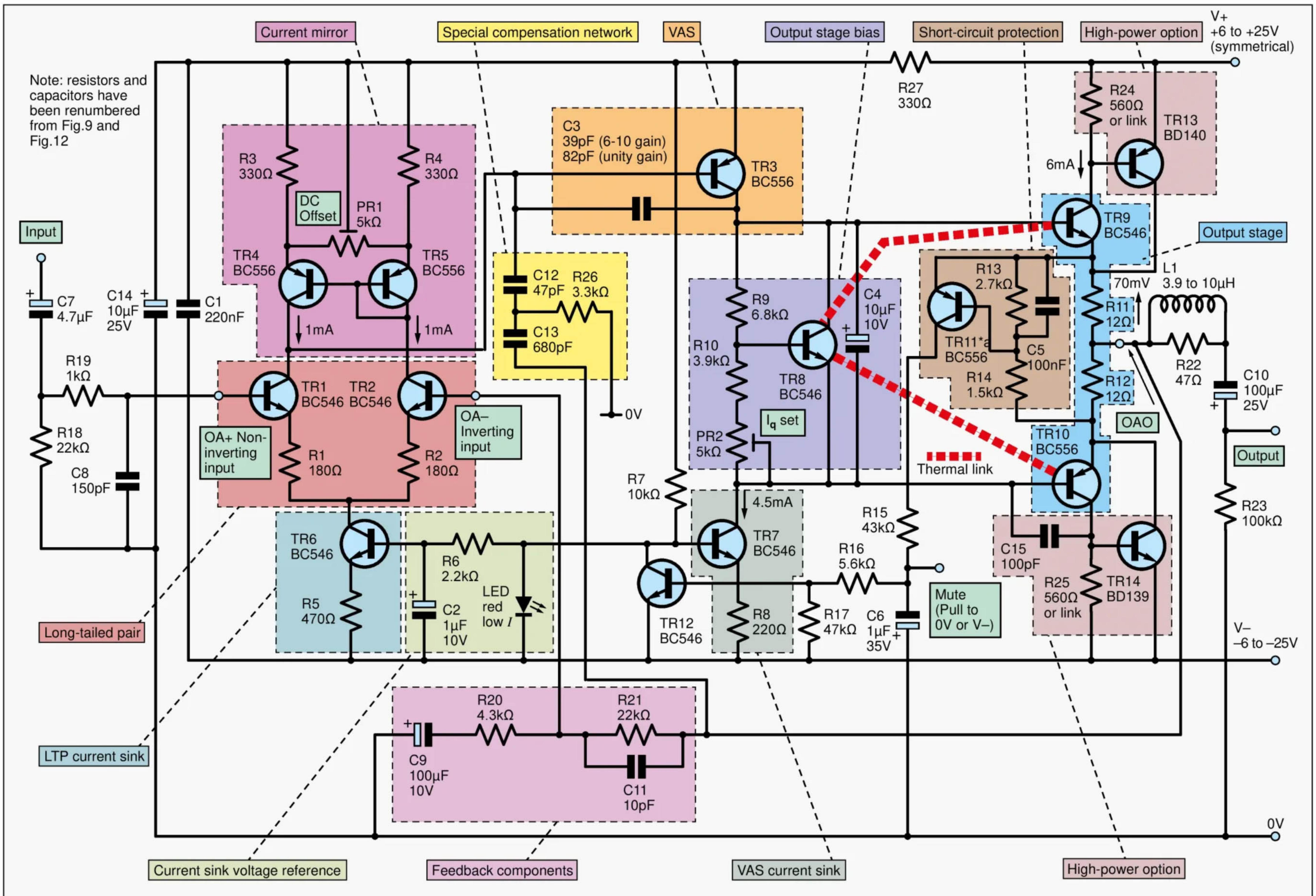
Comments or questions? Email Max at: **max@CliveMaxfield.com**

AUDIO OUT

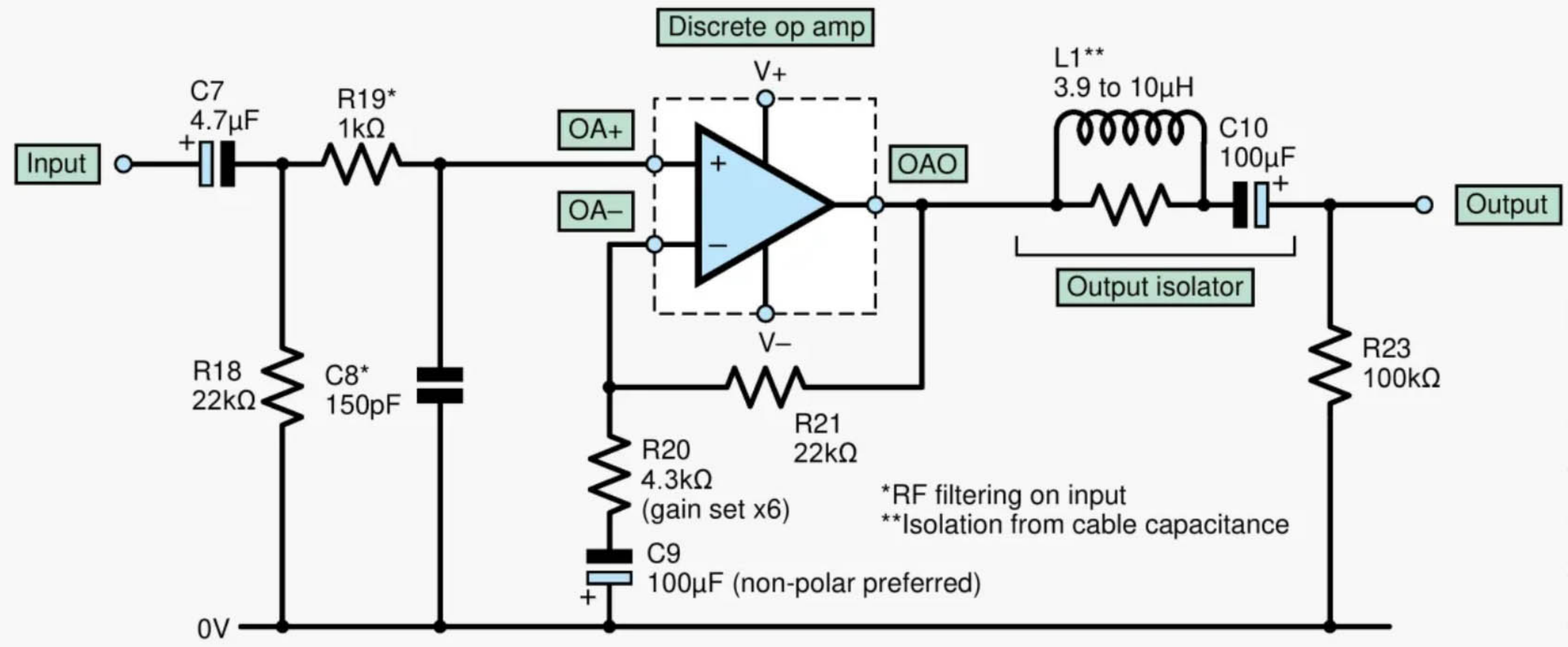
By Jake Rothman

Discrete audio op amp – Part 2

Last month, I introduced a novel project – my design for a *discrete* op amp (DOA) primarily intended for audio applications. This month, I want to further explain my thoughts on this circuit, especially the many options open to builders thanks to its non-integrated format. We are so used to thinking of op amps as little black boxes that we rarely consider what we could achieve by tweaking component types or values



Current mirror
Special compensation network
VAS
Output stage bias
Short-circuit protection
High-power option
V+ +6 to +25V (symmetrical)
Note: resistors and capacitors have been renumbered from Fig.9 and Fig.12
R27 330Ω
R24 560Ω or link
TR13 BD140
6mA
C3 39pF (6-10 gain) 82pF (unity gain)
TR3 BC556
R3 330Ω
R4 330Ω
DC Offset
PR1 5kΩ
Input
TR4 BC556
TR5 BC556
TR9 BC546
Output stage
L1 3.9 to 10µH
70mV
C7 4.7µF
C14 10µF 25V
C1 220nF
1mA
1mA
C12 47pF
R26 3.3kΩ
C13 680pF
R9 6.8kΩ
C4 10µF 10V
R13 2.7kΩ
TR11 BC556
C5 100nF
R14 1.5kΩ
R11 12Ω
R12 12Ω
R22 47Ω
C10 100µF 25V
R19 1kΩ
TR1 BC546
TR2 BC546
OA– Inverting input
0V
R10 3.9kΩ
TR8 BC546
Iq set
OAO
Output
R18 22kΩ
OA+ Non-inverting input
R1 180Ω
R2 180Ω
PR2 5kΩ
Thermal link
TR10 BC556
C8 150pF
R7 10kΩ
4.5mA
R15 43kΩ
R23 100kΩ
TR6 BC546
R6 2.2kΩ
LED red low I
TR7 BC546
R16 5.6kΩ
C15 100pF
R25 560Ω or link
TR14 BD139
R5 470Ω
C2 1µF 10V
TR12 BC546
R8 220Ω
R17 47kΩ
C6 1µF 35V
Mute (Pull to 0V or V–)
Long-tailed pair
V– –6 to –25V
R20 4.3kΩ
R21 22kΩ
C9 100µF 10V
C11 10pF
LTP current sink
0V
Current sink voltage reference
Feedback components
VAS current sink
High-power option



Discrete op amp
Input
C7 4.7µF
R19* 1kΩ
OA+
OA–
V+
V–
OAO
L1** 3.9 to 10µH
C10 100µF
Output
Output isolator
R18 22kΩ
C8* 150pF
R21 22kΩ
R20 4.3kΩ (gain set x6)
C9 100µF (non-polar preferred)
R23 100kΩ
0V
*RF filtering on input
**Isolation from cable capacitance

For low-power operation R24/R25 are links for high-power operation use 560Ω resistors

For high-power operation R11/R12 are 2.2Ω

For high-power operation fit C15 if using BD139/140

Fig.15. The DOA circuit with each stage defined by blocks. (Note, a few gremlins crept into last month's diagram of the overload part of the circuit in Fig.13. TR11 had its base and collector flipped; C6 was reverse polarised and must go to ground not V–. Also R17 should be 47kΩ, not 4.7kΩ.)

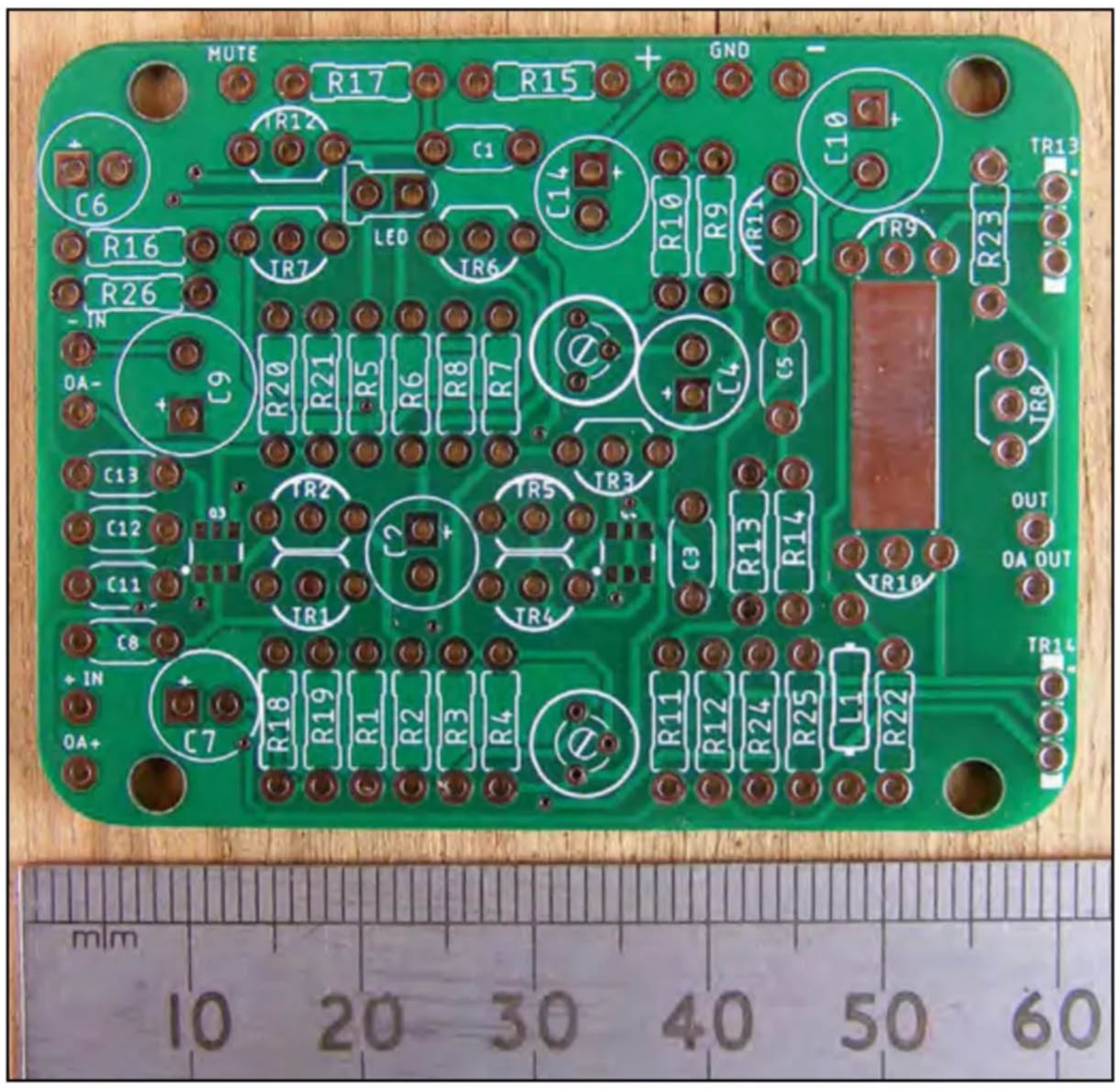


Fig.16. PCB for the DOA – we'll construct it next month.

– this is the great opportunity offered by a discrete version of the classic op amp.

Figure 13 update

The basic DOA circuit diagram was given in Fig.13 last month. In fact, there are a number of components to be added to enable various amplifiers (eg, inverting or non-inverting) to be built around the op amp on the PCB. The complete circuit is shown in Fig.15. There are specific inputs and outputs for the DOA (OA–, OA+ and OAO), and also for complete amplifiers with added feedback and coupling components.

Each of the DOA's internal stages are highlighted in Fig.15. These are the:

- Long-tailed pair difference amplifier (LTP)
- LTP current mirror load
- LTP current sink
- Voltage reference for LTP current sink
- Voltage amplifier stage (VAS)
- VAS constant current (sink)
- Output stage
- Output bias stage
- High-power output stage
- Short-circuit protection system

A quick note about the short-circuit protection system, which I didn't cover last month. This operates by sensing the voltage between the emitter (TR9 and TR10) resistors R11 and R12. When the voltage across TR11's base-emitter junction exceeds 0.6V, it turns on. This pulls the base of TR12 towards 0V turning it on, thereby shutting down the DOA.

Winners and losers

Before going any further I'd like to summarise the pros and cons of taking the discrete route, since it played a big role in how I designed the circuit.

Pros

- Lower noise if special input transistors are used
- Higher possible power rail voltages, giving more headroom
- Lower distortion into a low impedance load (<600Ω) – the result can effectively be a small power amplifier
- Lower noise when being driven by a low source impedance – eg, moving coil transducers
- Lower cost than specialist audio ICs
- Serviceable
- Upgrade possibilities – there are endless tweaking and experimenting opportunities
- Good-quality discrete PNP transistors are available, whereas most chip designs only have low-gain lateral PNPs unless expensive proprietary processes are used
- Currents and voltages can be adjusted and optimised to suit the application
- Low-cost, commodity parts can be used – some special chips cannot be imported into some locations/regions
- 'Discrete' has fashionable connotations in high-end audio – potentially higher profits!
- Large, high-quality NP0 capacitors can be used for compensation. On the other hand, ICs can only use poor-quality oxide-dielectric capacitors. In ICs the maximum capacitance value available is greatly reduced by the (relatively) huge amount of chip real estate consumed by capacitors
- Discrete designs are fun to build and highly educational for the home constructor
- You can put your name on it via the silk screen!

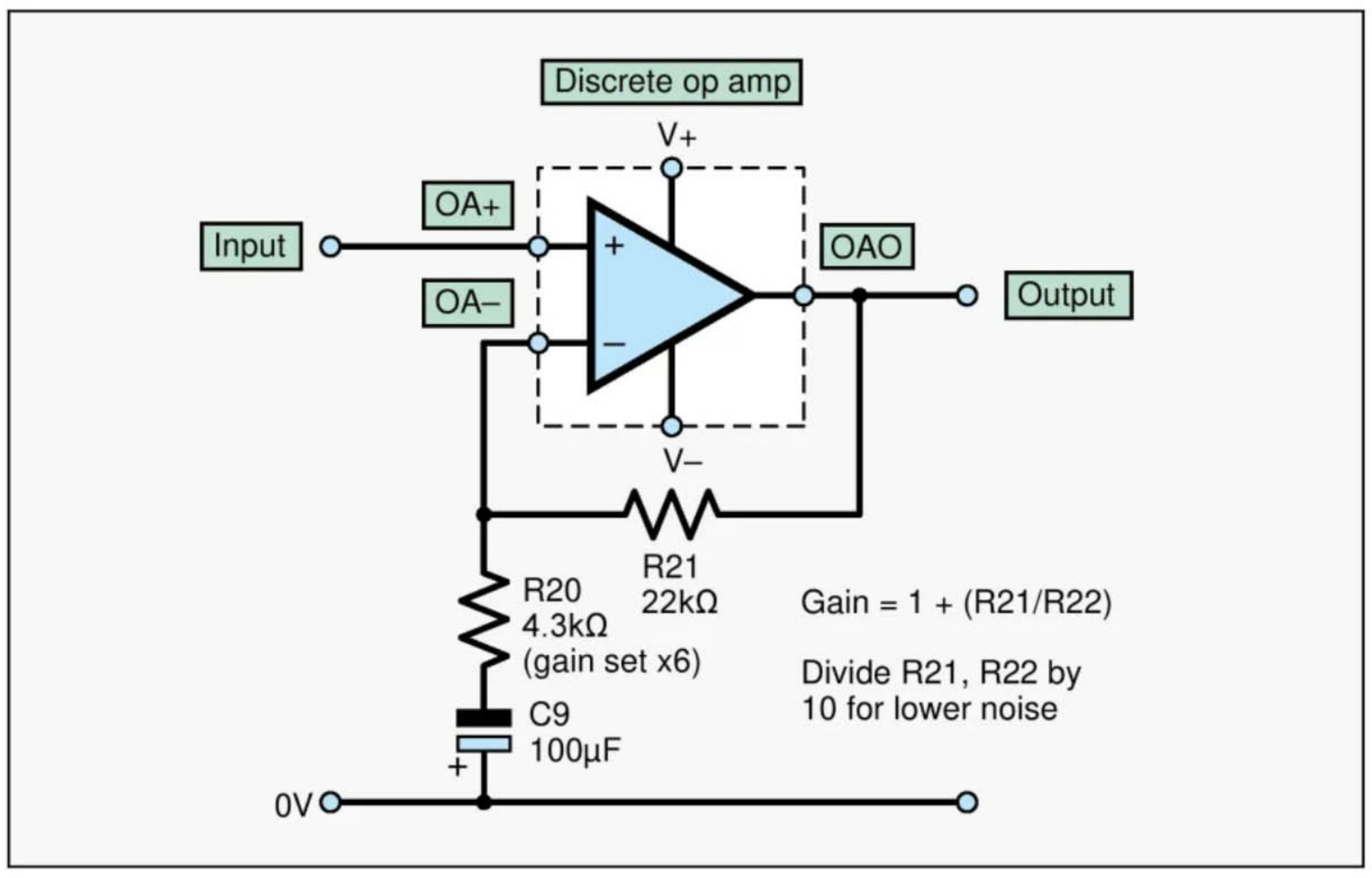


Fig.17. DOA configuration of non-inverting amp.

Cons

- High parts count
- Poorer reliability compared to ICs
- High labour cost, unless you build it yourself
- Large size, so not a good idea for systems using half a dozen op amps. The basic PCB is shown in Fig.16.
- Lower levels of protection, more vulnerable to overheating and rail-to-output shorts
- Higher power consumption
- Less consistent unit-to-unit performance
- Higher offset and input bias currents, so generally less suitable for precision DC instrumentation

Configuration options

One of the nice advantages of a PCB-based DOA design is that we can include on the same board space for standard op amp circuit 'external' components – for example, input and feedback resistors. This means on one board we can easily create some of the most common op amp circuits.

Non-inverting amplifier

This will possibly be the most popular option used by most audiophiles for pre-amps and headphone amplifiers. It is ideal as a pre-amp following a volume control. The configuration of the non-inverting op amp is shown in Fig.17. A finished PCB is shown in Fig.18.

Inverting amplifier

The inverting amplifier configuration is shown in Fig.19. This gives lower distortion than the non-inverting amplifier but at

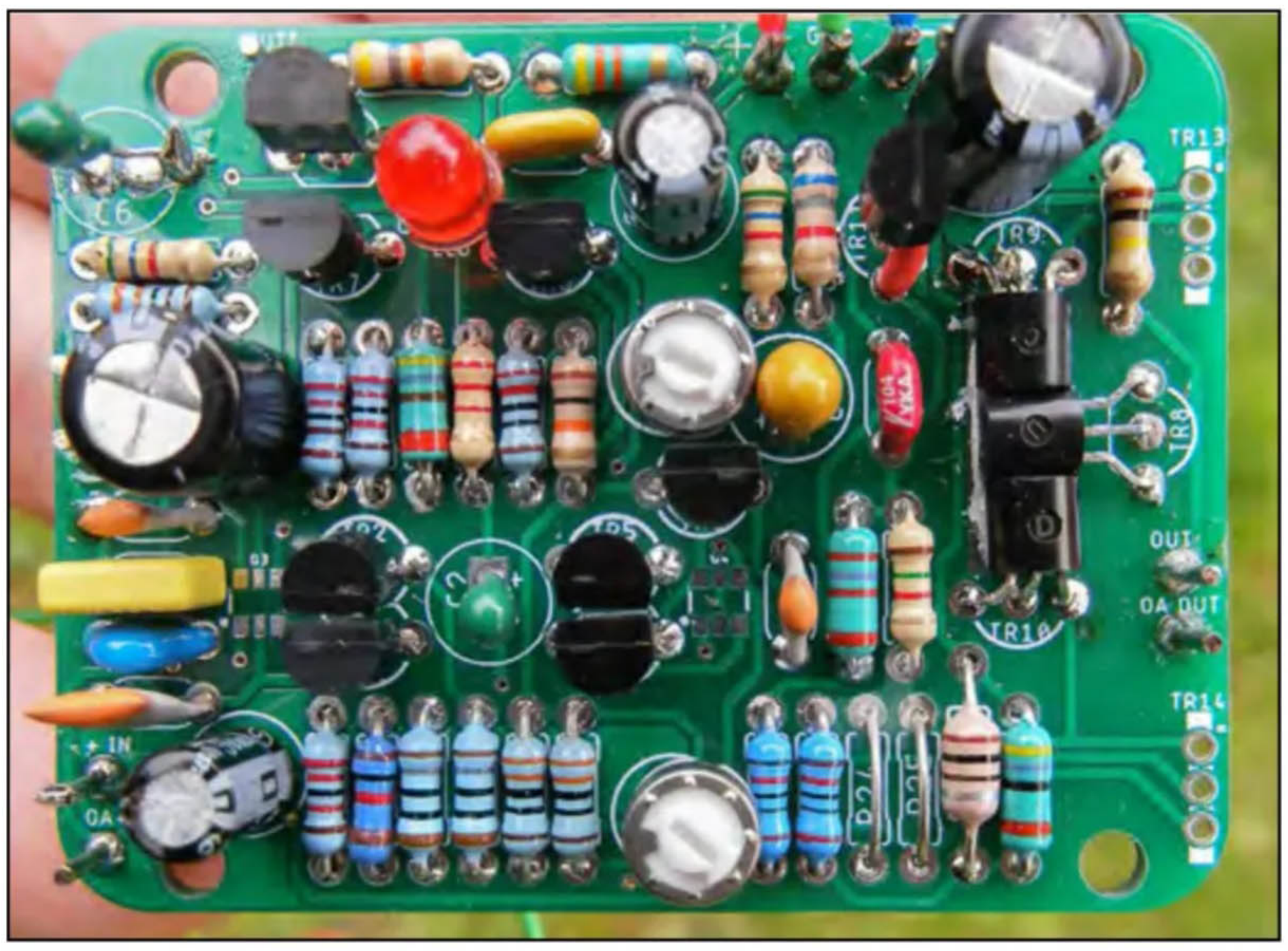
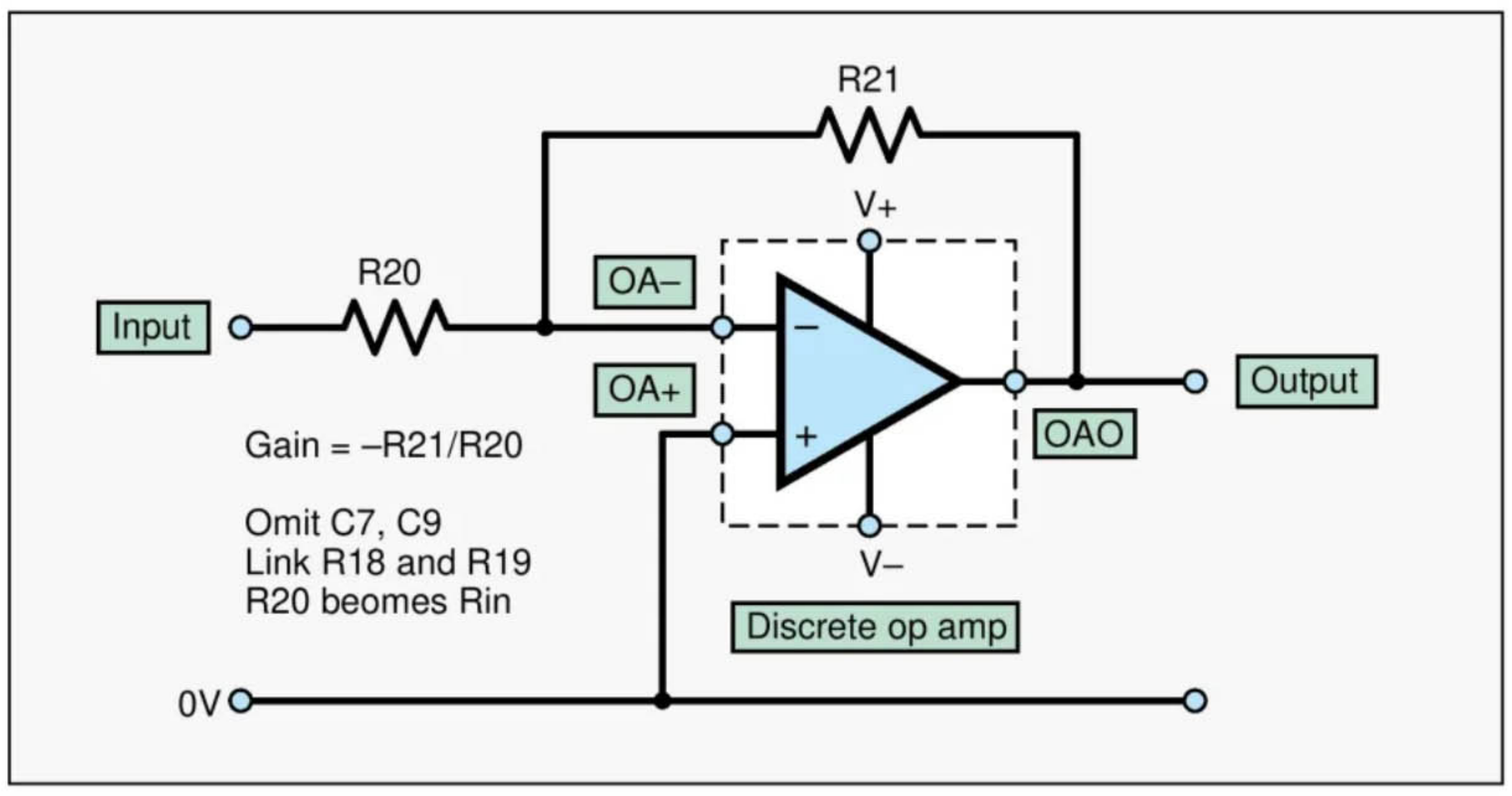


Fig.18. Finished PCB for low-power DOA. Note unused extra output transistor holes.


R21
V+
R20
Input
OA–
OA+
Output
OAO
Gain = –R21/R20
Omit C7, C9
Link R18 and R19
R20 beomes Rin
V–
Discrete op amp
0V

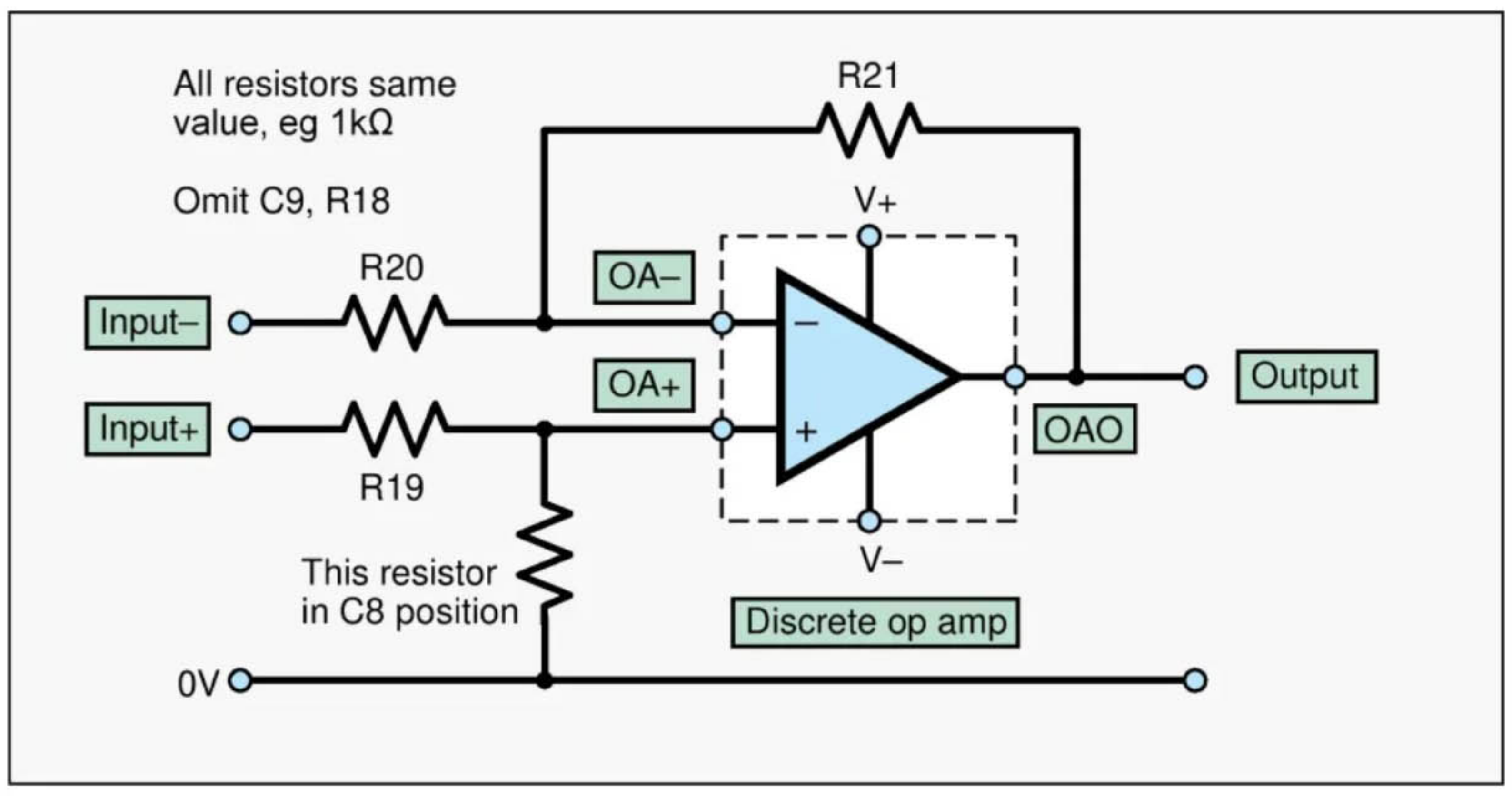

All resistors same value, eg 1kΩ
Omit C9, R18
R21
V+
R20
OA–
Input–
OA+
Input+
R19
Output
OAO
This resistor in C8 position
V–
Discrete op amp
0V

Fig.20. DOA configuration of differential amplifier.

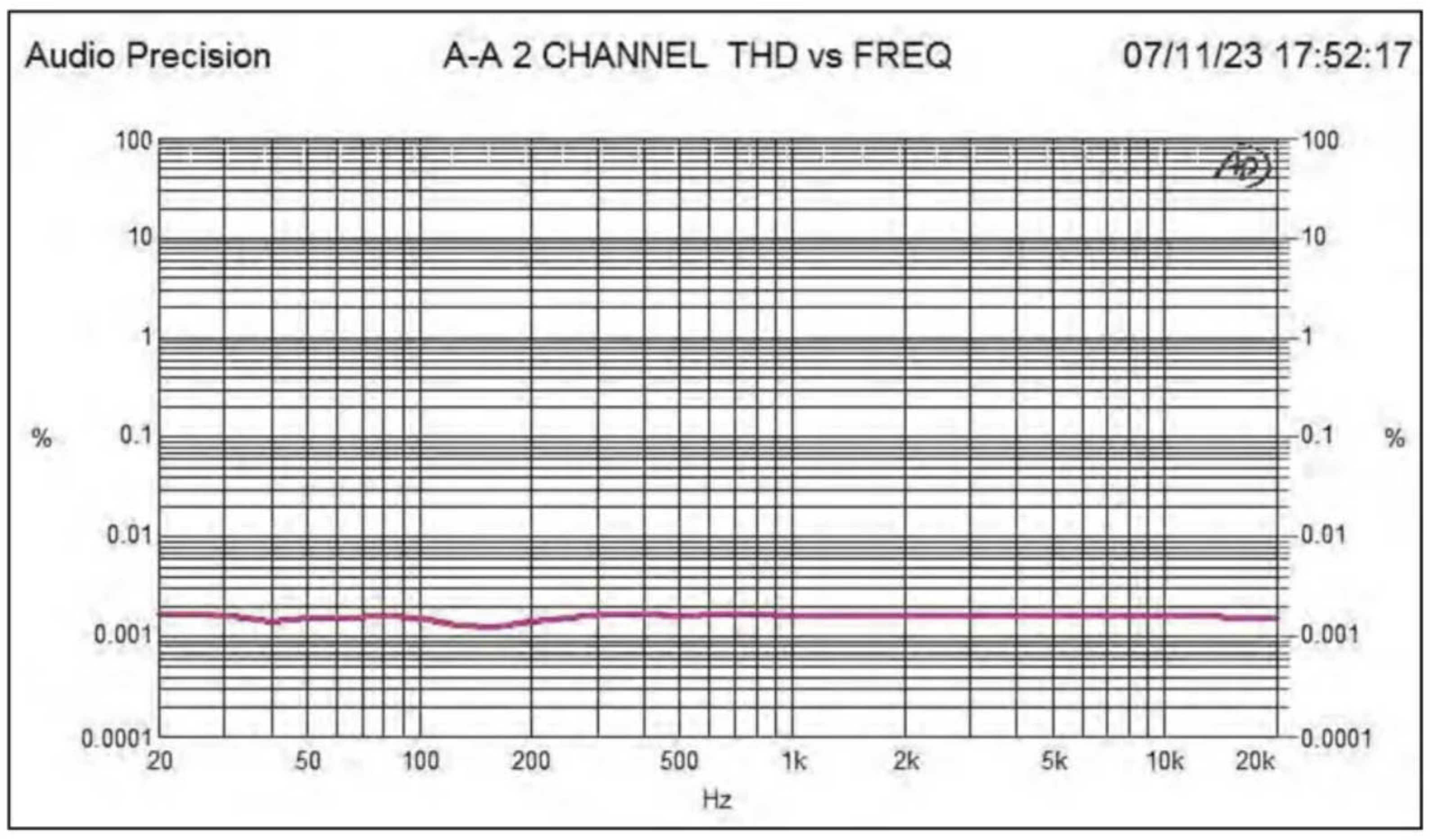


Fig.22. (above) Distortion plot of DOA with a load of 600Ω, ±25V PSU and 12$V_{pk\text{-}pk}$ output. (This includes noise.)

Fig.19. (left) DOA configuration of inverting amplifier.

the expense of higher noise from the input resistor R20. The inverting configuration is useful for mixing and distortion-cancelling negative output impedance transformer drivers (see *Audio Out*, February 2022).

Differential amplifier

The configuration for this is shown in Fig 20. It's useful for interfacing with low-impedance sources, such as moving-coil microphones.

Buffer

To be honest, this is just included for 'completeness' and I do not recommend using it! There's not much point using a full DOA as a follower, since the massive open-loop gain of an op amp is not needed. A simpler circuit using several transistors could be used, such as a diamond buffer, which can give 0.001% total harmonic distortion (THD). If you really want to make one then the configuration is shown in Fig.21.

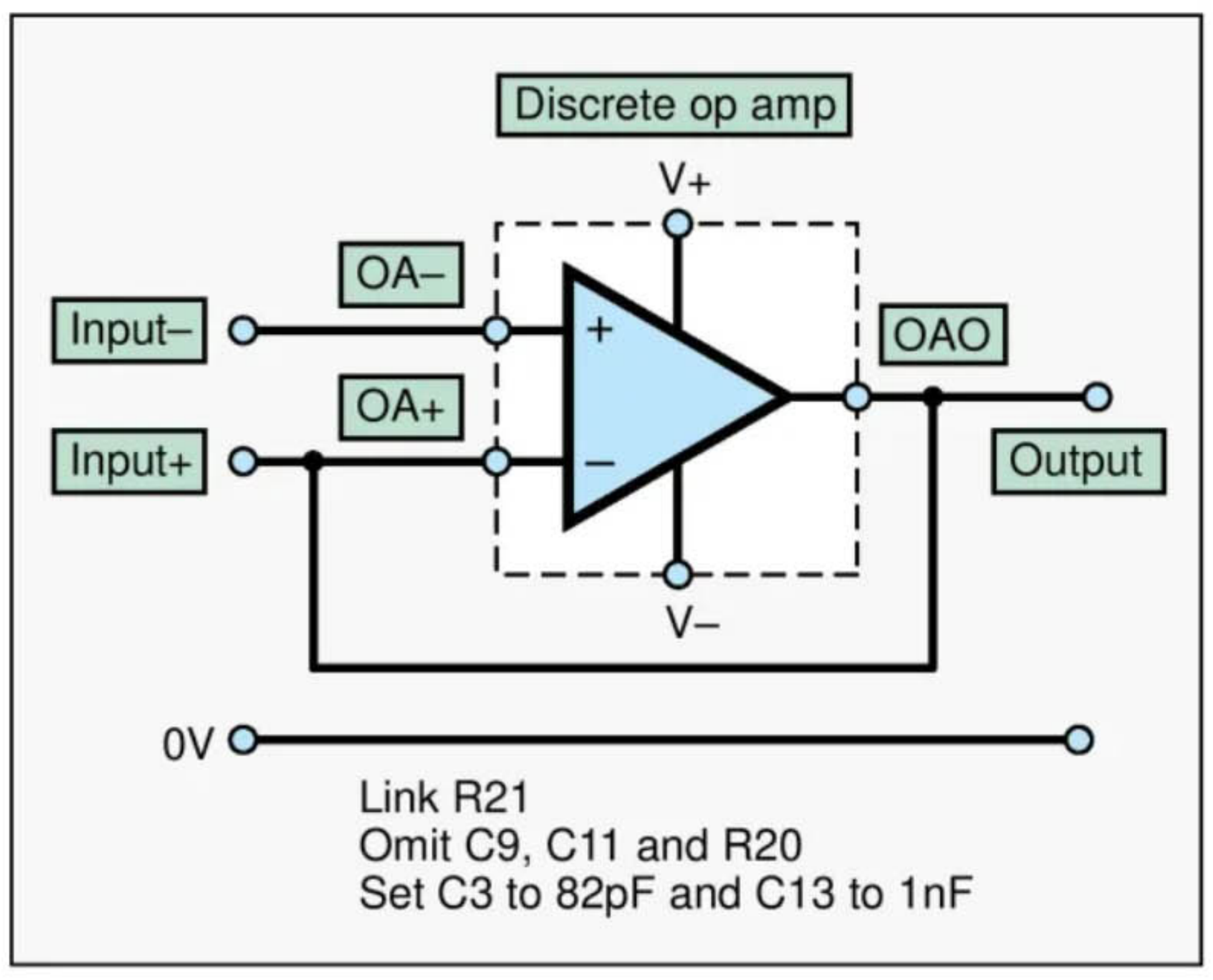

Discrete op amp
V+
OA–
Input–
OA+
Input+
OAO
Output
V–
0V
Link R21
Omit C9, C11 and R20
Set C3 to 82pF and C13 to 1nF

Fig.21 DOA configuration of buffer amplifier.

Discrete op amp specifications

Now that we have our DOA design, what is its performance like? Table 1 below shows a mini data sheet for the basic DOA using the BC546B and BC556 transistors. This is a preliminary specification – more refined data will emerge after I've tested multiple PCBs with different devices.

Transistor options

Many transistors are available with different H_{fe} grades, or put another way – ordinary, good and excellent versions.

Table 1. Discrete op amp 'data sheet'

Max supply voltage	±30V (recommended ±25V)
Output swing total	power rail minus 1.4V loss with no load
Total current consumption	12-18mA quiescent (output I_q set by user)
Max current, clipping into 330Ω	40mA
Absolute max current output	±100mA limit = 60mA
Input bias current	2.7µA
Noise voltage	1.5nV/√Hz with low-noise input transistors
Current noise	1.2pA/√Hz with low-noise input transistors
Optimum source impedance	1kΩ
Offset voltage, un-trimmed	±150mV, trimmed ±2mV
Using dual transistors (TR1/2/4/5)	<±10mV untrimmed
Max dissipation	600mW
Continuous power output	300mW into 330Ω
Open loop gain	>100,000x (no emitter resistors, R1 and R2)
Gain bandwidth product	13MHz
Slew rate	10V/µS proportional to transistor currents
Input impedance	>1MΩ
Output impedance (open loop)	20Ω
Min load impedance	330Ω (This can be reduced by a factor of 10 by adding extra output transistors.)
Power supply rejection ratio PSRR	–80dB negative rail –74dB positive rail (no decoupling network)
Distortion	<0.002% THD at 20Hz-20kHz into 600Ω (see Fig.22)

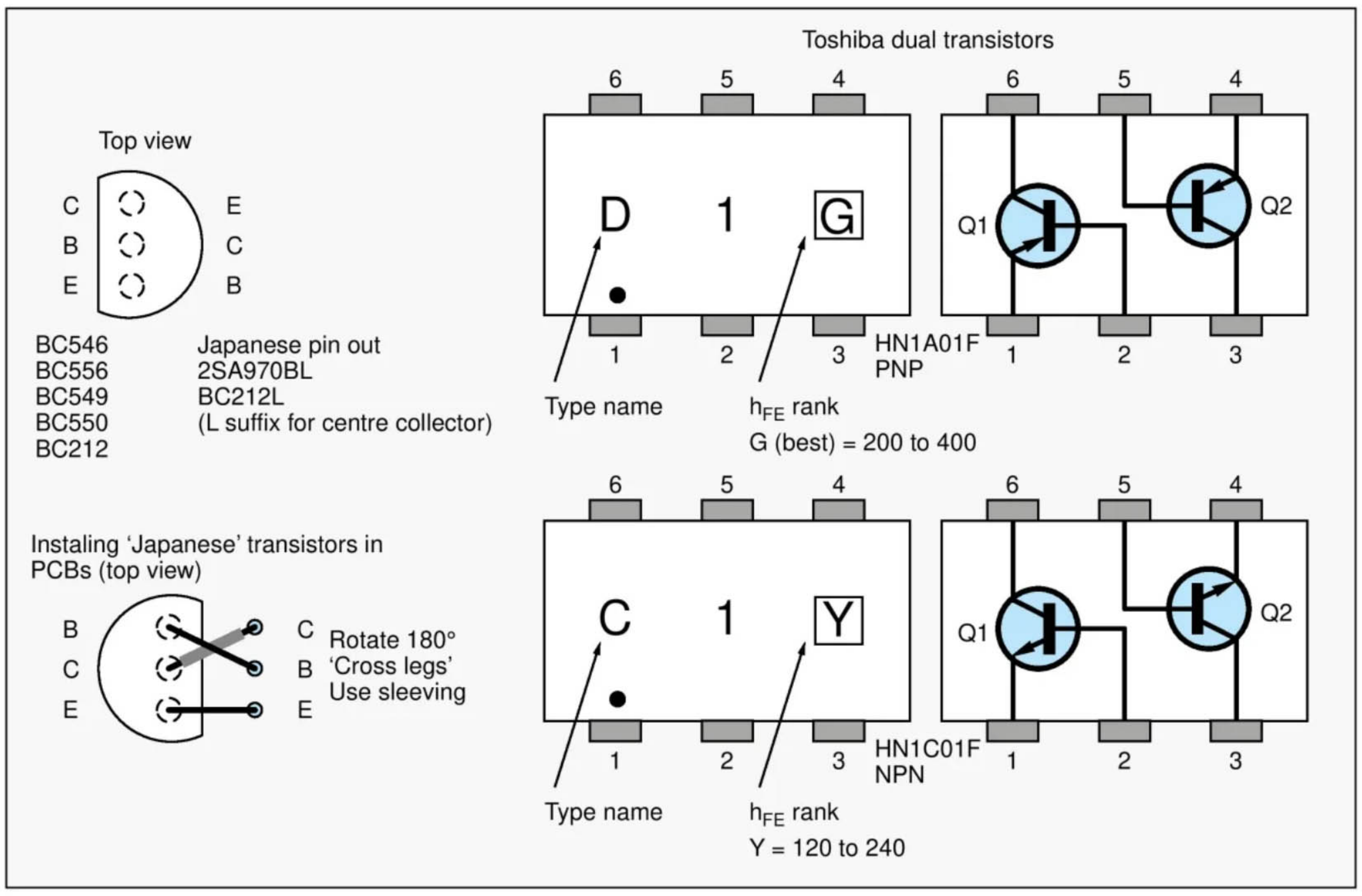

Toshiba dual transistors
Top view
C
B
E
E
C
B
BC546
BC556
BC549
BC550
BC212
Japanese pin out
2SA970BL
BC212L
(L suffix for centre collector)
Instaling 'Japanese' transistors in PCBs (top view)
B
C
E
C
B
E
Rotate 180°
'Cross legs'
Use sleeving
6
5
4
D
1
G
1
2
3
Type name
hFE rank
G (best) = 200 to 400
HN1A01F
PNP
Q1
Q2
C
1
Y
Type name
hFE rank
Y = 120 to 240
HN1C01F
NPN

Fig.23. Transistor packs and pin outs, and how to install centre-collector TO92 devices.

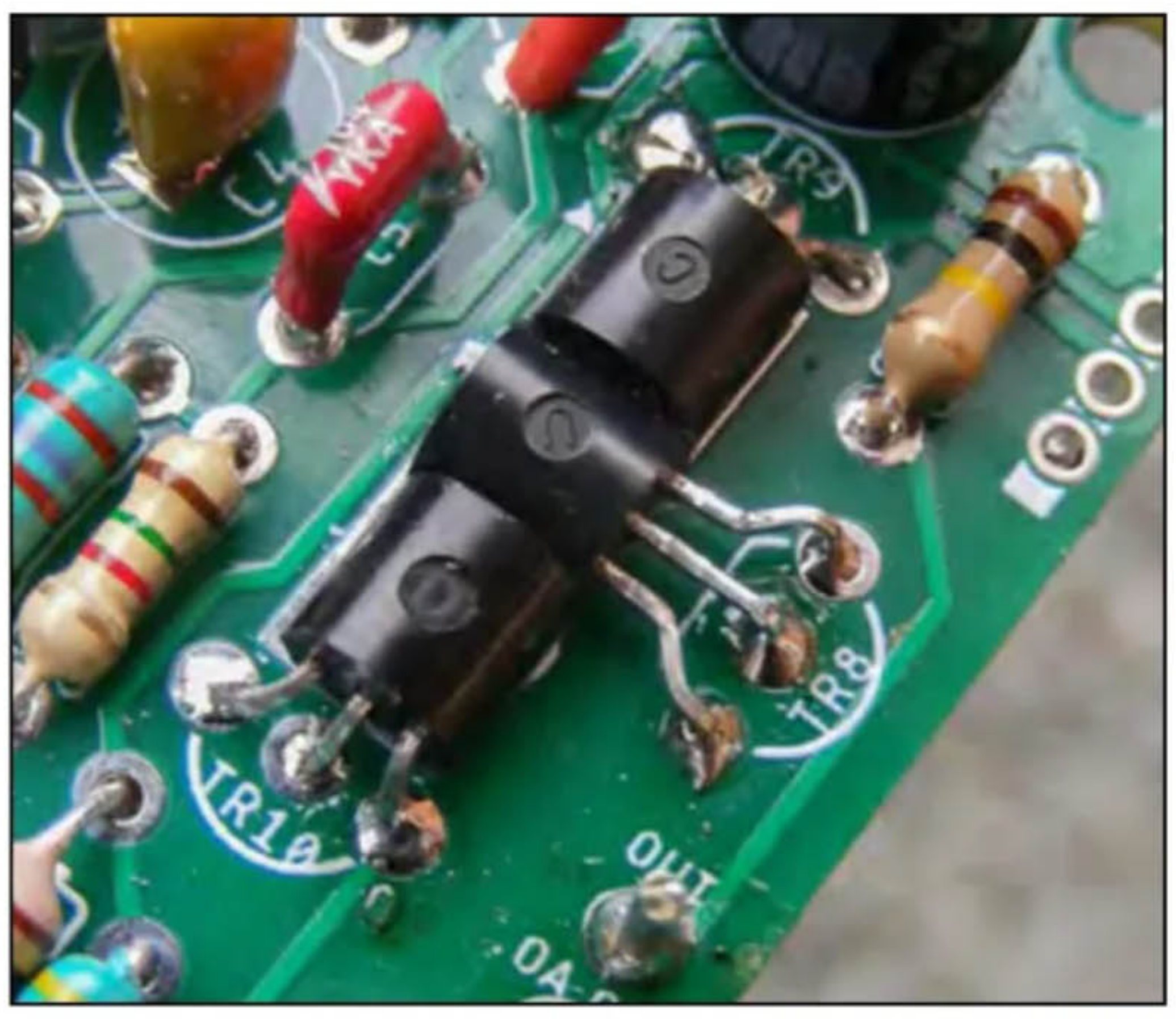


Fig.24. The output transistors and bias transistor are all thermally coupled together on a metal pad on the PCB.

For audio work, the higher H_{fe} values are preferred since they provide lower distortion. On graded BC series transistors (eg, BC549) the suffix 'A' is for the lowest H_{fe} values of 100-200; for 'B', 200-350; and for C, >350-600. If no grade is quoted then the gain can vary from about 100 to 600.

On Japanese Toshiba leaded small-signal devices , such as the 2SA970, 'BL' denotes the highest H_{fe} group. Unfortunately there seems to be a multitude of suffixes and consulting the data sheet is the only option. Toshiba, Hitachi and Sanyo generally make the best audio transistors if you can get them, but the circuit still gives excellent results with generic European types. Note that most Japanese transistors have their collector leads in the middle rather than the more common centre base, as shown in Fig.23. Once I've built several PCBs with different devices I'll have a better feel for the what the real benefits of Japanese transistors are.

The component option list below is in order of quality – in other words, upgrading the LTP circuit has the most beneficial effect.

Long-tailed pair (LTP)

For TR1 and TR2, low noise and matching is critical. BC546B is recommended for normal use. The BC549C (max rail ±25V) will give lower noise. For best results use 2SC2240BL, which have a very low 0.5dB noise factor (NF).

So long as the rail voltages do not exceed ±18V, a good choice would be the 2SC3068, which has an H_{fe} of 1600. This device is almost a possible substitute for JFETs, having a quarter of the normal bipolar transistor input bias current.

Current mirror

In a standard DOA current mirror, use BC556 PNP transistors for TR4 and TR5. For a small current mirror noise improvement, the BC550 has specified lower noise at 1-3dB NF, but a lower 45V V_{ce} (only an issue for high-power rails) The 2SA2362K is better still with 0.5dB NF.

Dual devices

Dual devices are worth considering because they automatically come with well-matched transistors. I was pleased to discover these dual devices from Toshiba: HN1C01F-GR NPN for TR1/TR2, and HN1A01F-GR PNP for TR4/TR5. They can be mounted either way round (see Fig.23) which makes soldering a little less error prone. They are available from Mouser in SOT26-6 6-pin packs, which are 'easy' to solder. Last, but not least, they are cheap.

VAS

The VAS PNP transistor TR3 is subjected to the full rail voltage, so it will need to be rated at a minimum V_{ce} of 65V. It also needs a high H_{fe} to avoid loading the current mirror. Higher voltage types generally have lower Early effect distortion, but with lower H_{fe}, which then increases the loading on the current mirror. Ultra-low noise is less important, since it mainly amplifies the first stage noise. A BC556 is acceptable, but the BC556B has higher H_{fe}. The Japanese 2SA2362K device is rated at 120V with an H_{fe} of 350.

The associated current sink transistor (TR7) needs a high voltage rating, but its H_{fe} and noise specifications are not important. A BC546 is fine here.

Output stage

For the low-power output DOA, TR9 and TR10 are a complementary NPN/PNP pair. High current and voltage capability are the main requirements, along with reasonable H_{fe} (>200). BC546 and BC556 are only rated at 100mA. BC639 and BC640 are rated at 80V 600mA, but their low H_{fe} of 80-120 means there may be a need to increase the VAS current. ZTX651 and ZTX751 are similar alternatives, rated at 65V 2A.

Output stage bias generator

In this circuit for TR8, it's best to use the same NPN device as in the output pair (TR9). This will give better thermal tracking since their V_{be} values will be similar. So, if you are using ZTX output devices, use a ZTX651 for TR8. Note how the output transistors TR9 and TR10 are all thermally coupled together with the bias transistor TR8, as shown in Fig.24.

The remaining transistors (TR8/11/12) are uncritical (low voltage, low current, low H_{fe}). Old timers like the NPN BC108 and BC182 can be used for TR6 and

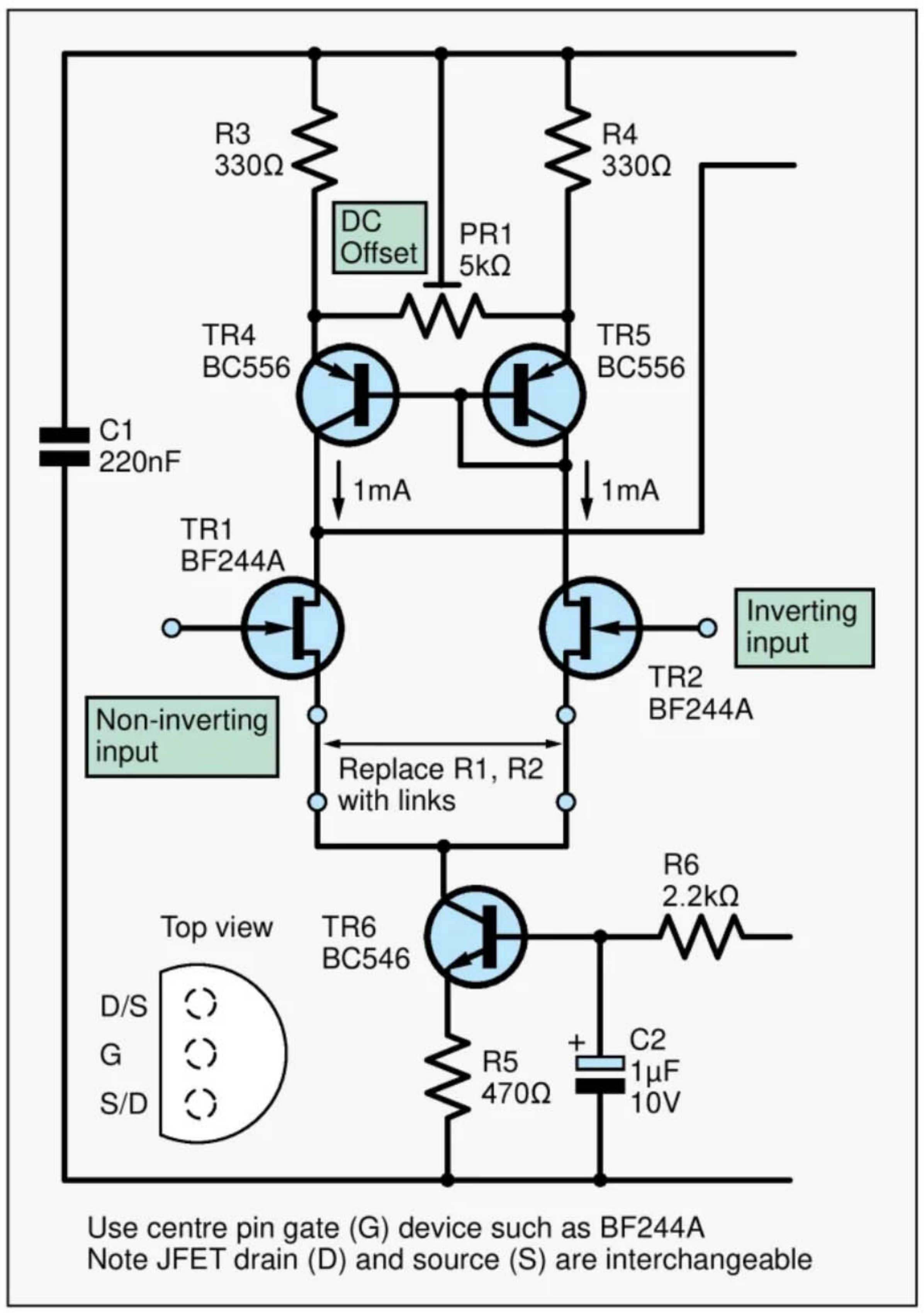

R3
330Ω
R4
330Ω
DC Offset
PR1
5kΩ
TR4
BC556
TR5
BC556
C1
220nF
1mA
1mA
TR1
BF244A
Inverting input
TR2
BF244A
Non-inverting input
Replace R1, R2 with links
R6
2.2kΩ
Top view
TR6
BC546
D/S
G
S/D
R5
470Ω
C2
1μF
10V
+
Use centre pin gate (G) device such as BF244A
Note JFET drain (D) and source (S) are interchangeable

Fig.25. Installing FETs on the input LTP stage.

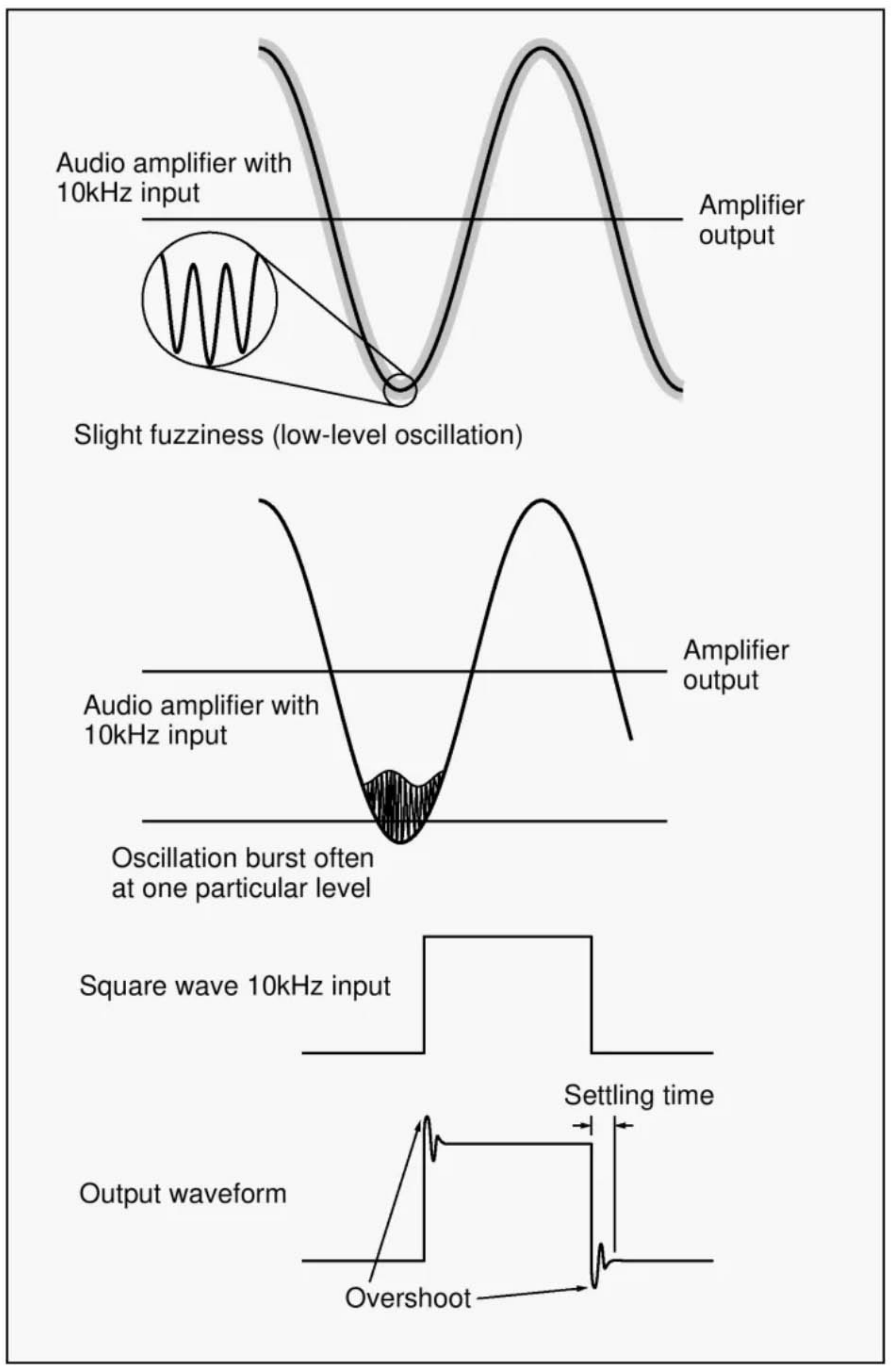

Audio amplifier with
10kHz input
Amplifier
output
Slight fuzziness (low-level oscillation)
Amplifier
output
Audio amplifier with
10kHz input
Oscillation burst often
at one particular level
Square wave 10kHz input
Settling time
Output waveform
Overshoot

Fig.26. Amplifier on the verge of oscillation.

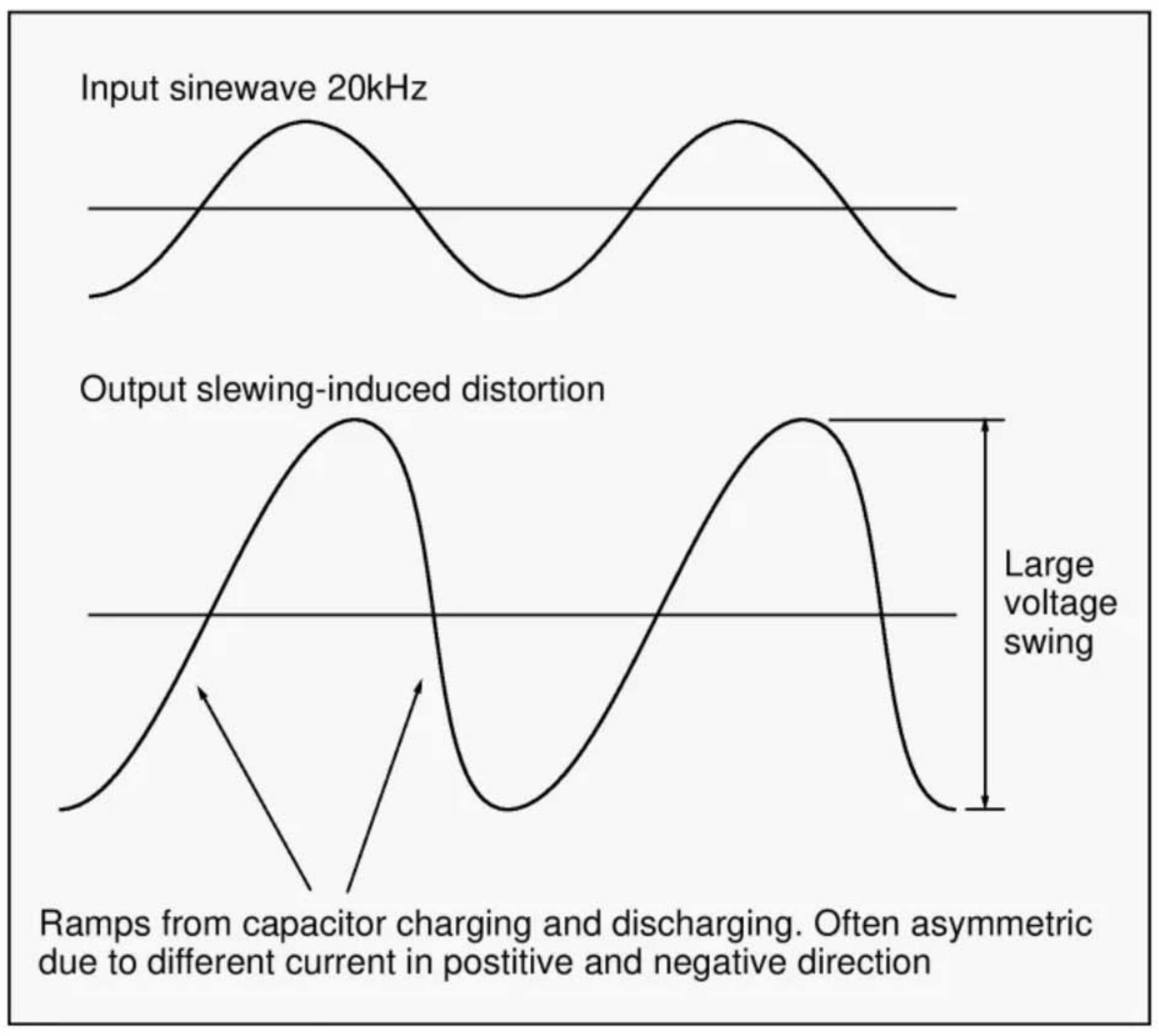

Input sinewave 20kHz
Output slewing-induced distortion
Large
voltage
swing
Ramps from capacitor charging and discharging. Often asymmetric
due to different current in postitive and negative direction

Fig.27. Effect of overloading the input stage by too large a value for C3.

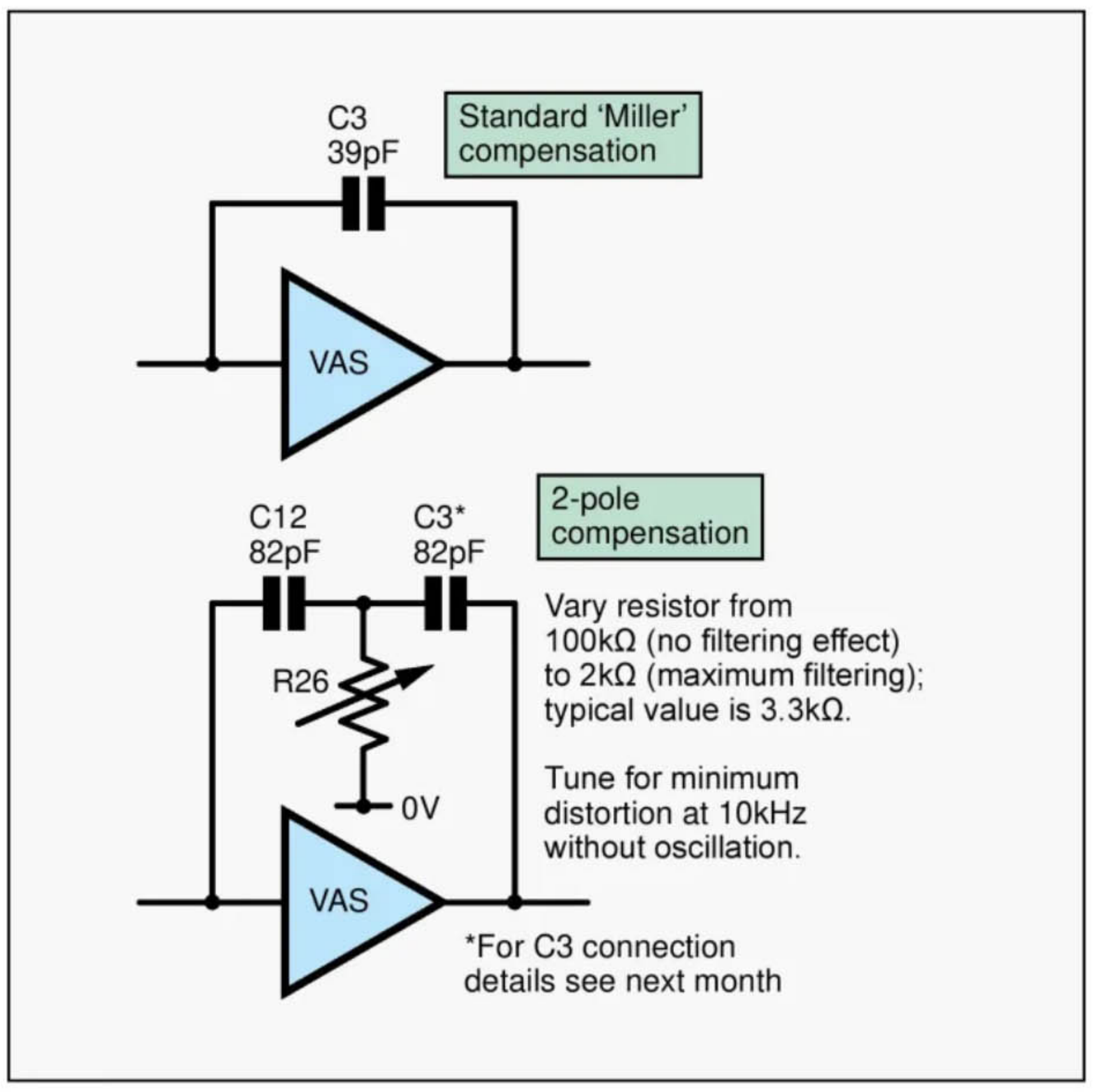

C3
39pF
Standard 'Miller'
compensation
VAS
C12
82pF
C3*
82pF
2-pole
compensation
R26
0V
Vary resistor from
100kΩ (no filtering effect)
to 2kΩ (maximum filtering);
typical value is 3.3kΩ.
Tune for minimum
distortion at 10kHz
without oscillation.
VAS
*For C3 connection
details see next month

Fig.28. Second-order compensation.

TR11. BC178 and BC212 could be used for PNP TR12.

FET input

The most important possible tweak/upgrade to the standard DOA (Fig.15) is using FETs for the LTP input transistors (TR1/2) shown in Fig.25. It's worthwhile substituting N-channel JFETs here to produce high input impedance (>1MΩ) and low bias currents.

The gate becomes the base connection and since JFETs are symmetrical devices, it does not matter which way the source and drain pins go into the emitter and collector holes. The voltage noise is twice as much for generic JFETs compared to bipolar transistors, but the current noise and bias currents are very low.

It's more difficult to match JFETs, since their spreads are much higher than bipolar transistors. The distortion is also higher, although using BF244A FETs on a ±25V supply the difference becomes negligible.

FET inputs are particularly good for active filters and circuits using potentiometers without coupling capacitors, such as amplifiers following high-impedance volume controls. The 2SK170 is the best device. Older European low-noise JFETs, such as the BFW10 are also good. If you are rich, consider dual matched JFETs from InterFET.

High power output option

A pair of extra output power transistors (TR13 and TR14) can be added to the existing output stage on the PCB, which then becomes the driver stage. This enables more difficult loads to be driven down to 50Ω. This will be covered next month.

Stability tip

Remember that output stages can oscillate with capacitive loads, such as screened audio leads and scope probes. This is normally compensated for by inserting a resistor (39Ω to 120Ω) in the output (R22). This unwanted additional output impedance can be mitigated by putting an inductor (L1) in parallel with the resistor.

Another stability tip involves adding a small 'phase lead' capacitor of 4.7 to 47pF (C11). This is often placed across the feedback resistor (R21), and compensates for any stray capacitance to ground from the inverting input. It is best optimised by looking for any overshoot on a high frequency (>10kHz) square wave. Too much capacitance will cause low-pass filtering and round-off the square wave.

Compensation options

In all amplifiers using negative feedback, a capacitor (C_{dom}, C3 on the DOA board) is needed to stabilise the loop by setting a dominant high-frequency roll-off. The more feedback, or lower the closed-loop gain, the bigger the capacitor. The single compensation capacitor C3 has to be 82pF for a unity gain (buffer), such as in a Baxandall tone control, but 39pF for a gain of 6-10 and scaled accordingly:

Gain	*C3*
1 (unity)	82pF
6-10	39pF
10-20	27pF
20-50	15pF

Do remember, these are guidelines only, you still need to check stability for your board, application and batch of transistors.

C3 can be optimised for different gains and transistor spreads by using a 5.5 to 65pF trimmer capacitor instead of C3. Remember to increase it by at least 30% beyond the point where oscillation stops, just in case changes in temperature and loading cause more compensation to be needed. Instability often occurs at only some points in a sinewave, as shown in Fig.26. Stability compensation includes so many unknown variables it often becomes a fiddle fest. This is why you see odd ceramic capacitors soldered under the board in many commercial amplifiers.

Another thing that has to be watched is that this capacitor does not get too big (over compensation), because it may then overload the input stage. There has to be enough current available to cleanly charge or discharge it on rapidly changing signals. This can be tested by driving the amplifier to almost full output voltage at 20kHz and is revealed if the output sinewave suffers from slew limiting and becomes an asymmetrical ramp wave, as shown in Fig.27.

Second-order compensation

If you want an amplifier with the lowest overall high-frequency distortion, then to achieve more overall feedback at high frequencies, C3 is upgraded to a second-order compensation network. This increases the slope of the compensation curve, so it can be moved to a higher frequency before oscillation occurs, allowing the feedback factor to be higher at higher frequencies. This gives lower distortion at high frequencies. It was used in the *Tiny Tim Amplifier* (*PE*, January 2015). It normally adds another capacitor in series with C_{dom} (C3) with the junction tied to earth via a resistor to

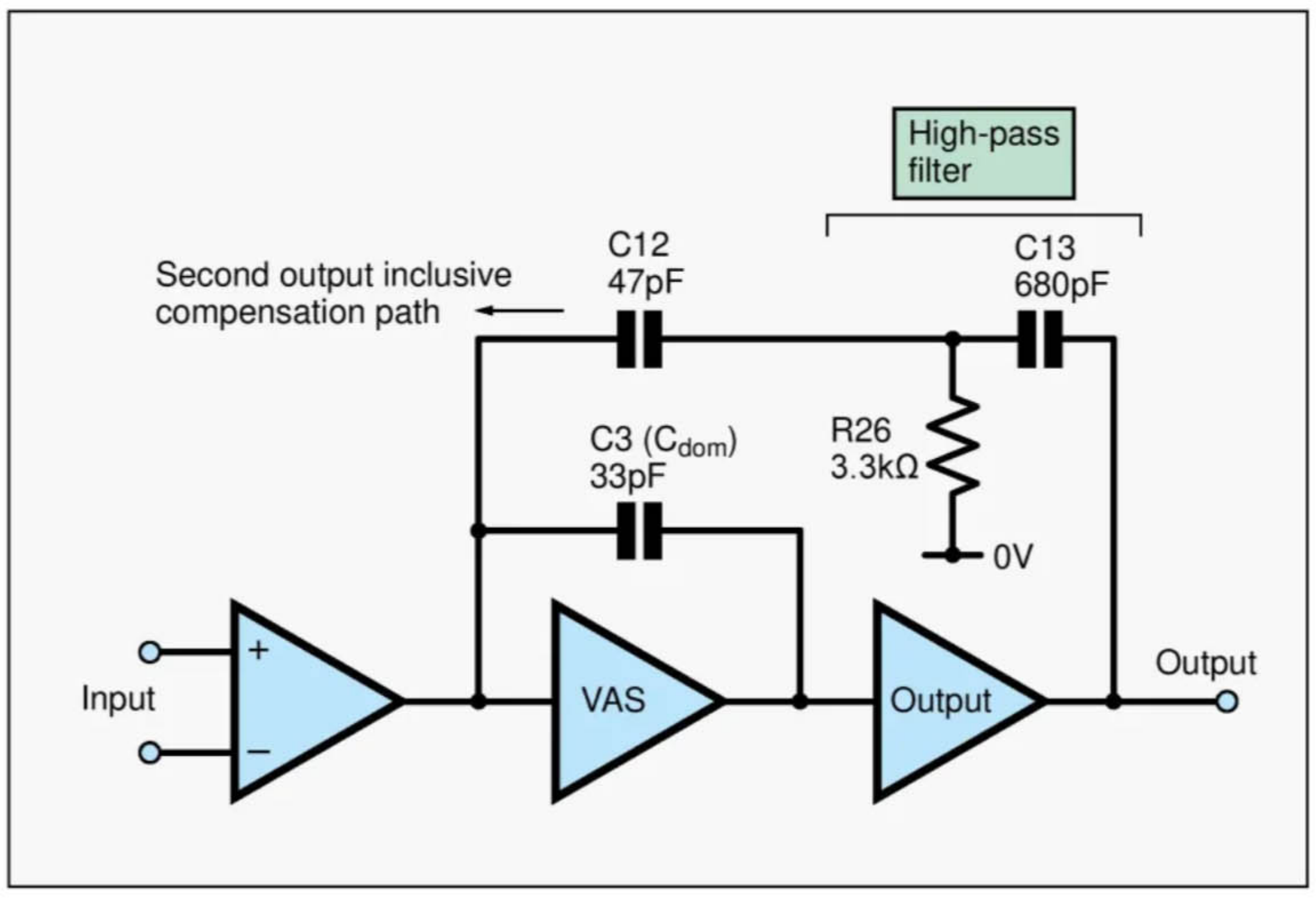


Fig.29. Inclusive Baxandall second-order compensation. You couldn't do this on a chip.

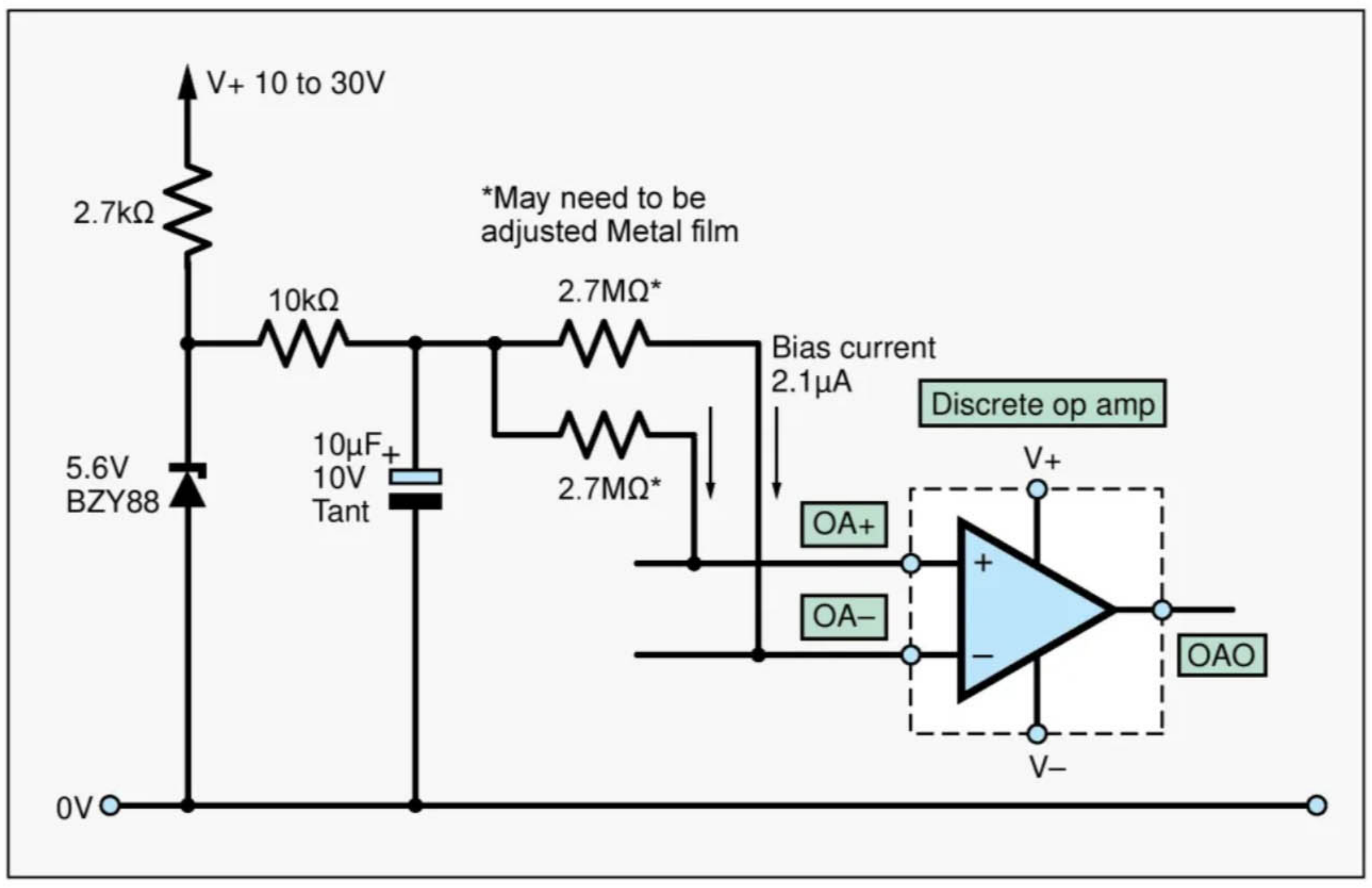


Fig.30. Input current bias compensation – take care with noise injection.

provide the extra high-pass slope. This scheme is shown in Fig.28.

Inclusive Baxandall second-order compensation

Normally, in amplifiers the compensation capacitor feedback loop cannot include the output transistors. This is because large transistors, such as the TIP31, are rather slow, often with a transition (unity-gain) frequency (F_t) of only 3MHz. This phase lag from the output transistors can cause oscillation. In DOAs, the smaller output devices used usually have an F_t at least 20x higher, allowing the compensation loop to include the output devices. This enables crossover distortion to be more effectively reduced by the overall negative feedback, minimising the distortion rise often seen around 10kHz. It also seemed a good idea to combine this with second-order compensation.

This compensation scheme is shown in Fig.29 and it can be seen that a signal from the output is fed into C13, rather than from the output of the VAS. This signal is high-pass filtered by C12 and R26 to get the second-order slope. Since there is now feedback summed from two points, the VAS feedback can be reduced by decreasing C3 to 33pF. This reduces the loading on TR1. The overall effect is to provide inclusive Baxandall second-order compensation.

Note that for gains other than 10, the values of C3, C12 and C13 will all have to be scaled; more capacitance for less gain. I will cover this in more detail next month. Remember to only use low distortion dielectric capacitors such as NP0 ceramic, polypropylene or polystyrene for C3, C12 and C13. If you use low voltage SMT X7R ceramic types, they cause the distortion we're trying to reduce.

Optional off-board input bias current compensation

For a bipolar transistor version of the DOA, bias current flows into the base of the LTP input transistors (DOA input terminals). This causes a small negative offset which is why the electrolytic capacitors (C7, C9 and C10) in Fig.15 are all oriented with the negative terminal facing into the DOA. If you have an application that requires cancellation of these input bias currents then you can add on the circuit shown in Fig.30 (an offboard add-on). It works by injecting a positive current from a low-noise source. With PNP transistors the current has to go the other way.

Off-set adjustment

The voltage input offset trimmer (PR1) can either null the output (OAO) offset or balance the LTP collector (TR1/2) currents for minimum distortion. It can't optimise both at the same time. Sonically, even-order distortion is much more subtle than the effect of earlier asymmetrical clipping, so trim for minimum OAO voltage offset. It should be possible to trim this to within ±2mV.

Quiescent current adjustment

The output stage quiescent current (I_q) must be set carefully with PR1. If set too high the output transistors will burn out. Always set for maximum resistance (fully clockwise) before turning on. Gradually increase until 70mV is obtained across each 12Ω emitter resistor (R11 and R12) giving 6mA. This current can be optimised for lowest distortion and current consumption for various loads. More details will be provided next month.

Input and output protection

Another optional off-board add-on is back-to-back diodes across the DOA inputs to protect TR1 and TR2 from reverse biasing of their base-emitter junctions. This can permanently damage them, increasing noise levels. Also, reverse-biased diodes from output to rails will protect the output transistors from reverse voltage spikes from inductive loads such as output transformers and loudspeakers. This protection is shown in Fig.31.

Normally a DOA is built into a system and doesn't need these diodes, but in the less common situation where you are directly driving an inductive load or are using phantom power then consider adding them.

Recommended power supply

I view an amplifier as a power supply modulator. If the power supply is poor quality, then so will be the amplifier's output. Unlike power amps, a *regulated* supply is always used for op amps, so the voltage ratings of the transistors are less critical because the rails are better specified. For the DOA I recommend my special low-noise audio power supply described in *Audio Out*, April 2022. A suitably scaled-up version providing ±25V is shown in Fig.32. Note that to set the regulators to 25V, unusual resistor values (R7 and R8) are needed. E96 series 1% metal-film resistors are now cheap and are available from Mouser and Farnell. If you want, 2.2kΩ 0.5W and 82Ω resistors can be connected in series which will come closer to 25V than the E96 resistors.

All amplifiers have a power supply rejection ratio (PSRR), that is how much noise on the power rail is attenuated at the output. This parameter is normally specified in dB at a particular frequency. In this case, it is around –75dB at 1kHz. With this design, the PSRR is 6dB worse on the positive rail because signals from the rail can be directly injected into the emitter of TR3. This is why an additional power supply decoupling capacitor is provided: C14 on the DOA.

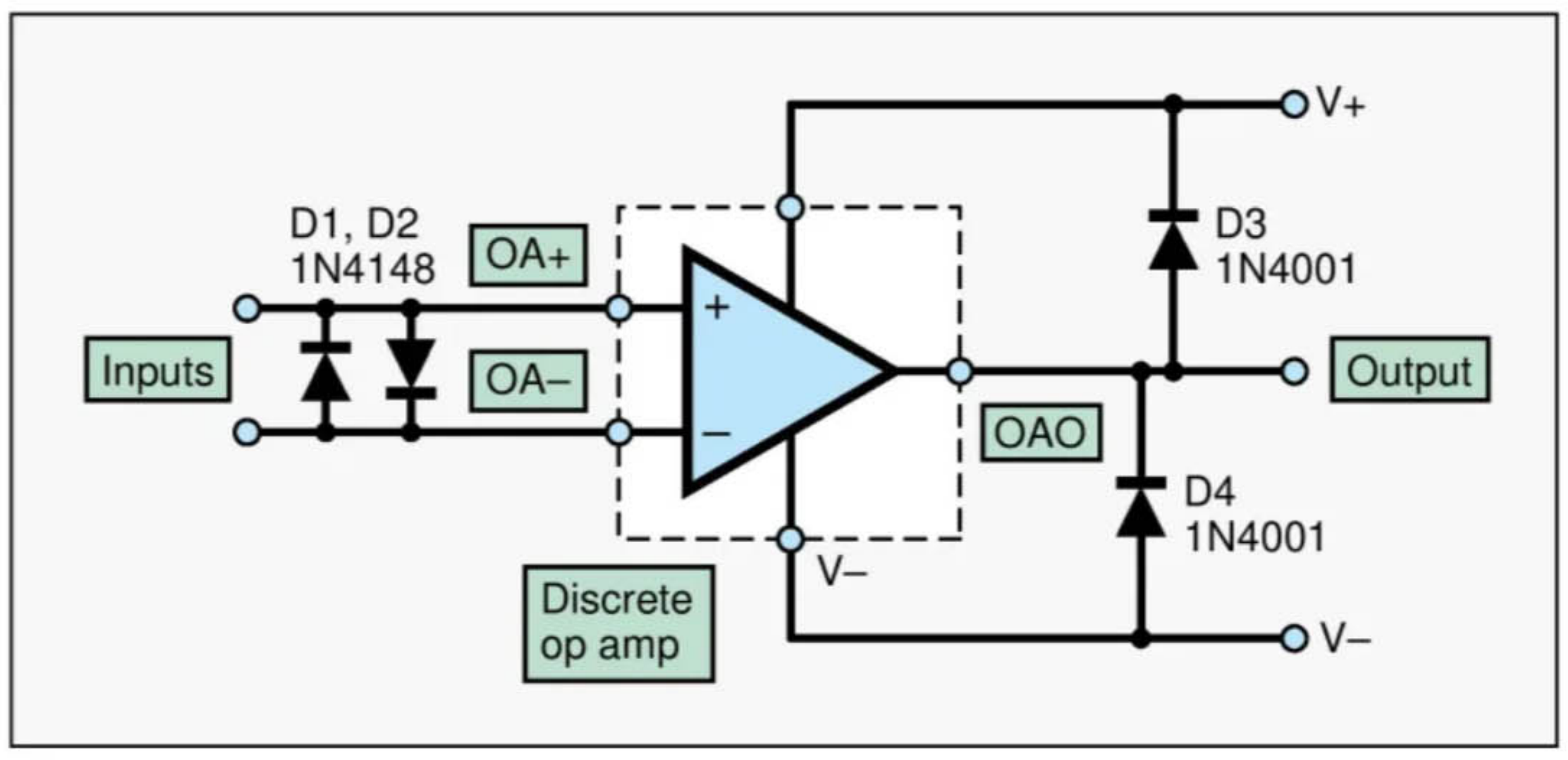


Fig.31. Protection of inputs and outputs from voltage spikes.

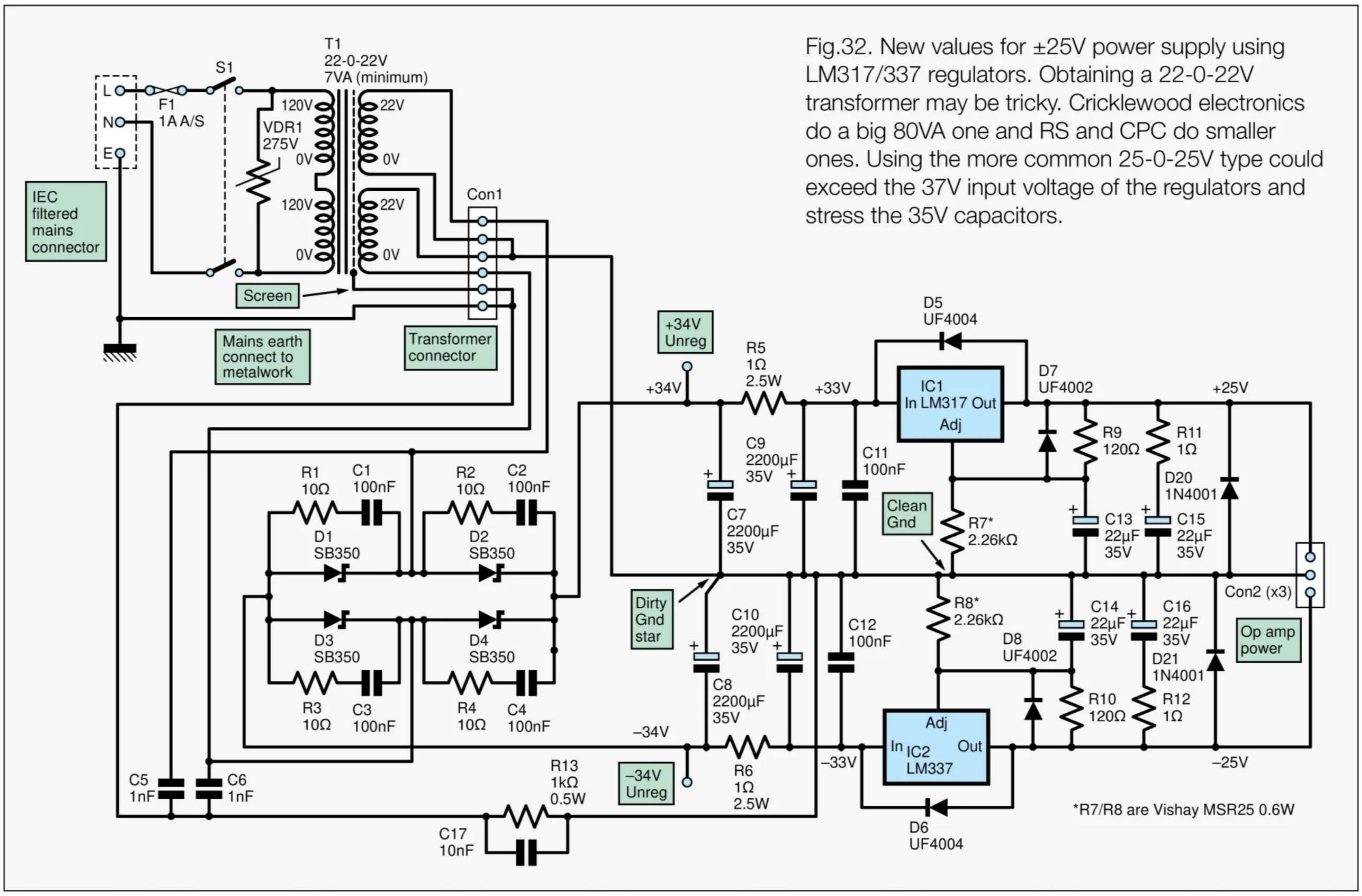

T1
22-0-22V
7VA (minimum)
S1
L
N
E
F1
1A A/S
VDR1
275V
120V
0V
120V
0V
22V
0V
22V
0V
IEC filtered mains connector
Screen
Con1
Mains earth connect to metalwork
Transformer connector
+34V Unreg
R5
1Ω
2.5W
+34V
+33V
D5
UF4004
IC1
In LM317 Out
Adj
D7
UF4002
+25V
R9
120Ω
R11
1Ω
D20
1N4001
C9
2200µF
35V
C11
100nF
C7
2200µF
35V
Clean Gnd
R7*
2.26kΩ
C13
22µF
35V
C15
22µF
35V
Con2 (x3)
R1
10Ω
C1
100nF
D1
SB350
R2
10Ω
C2
100nF
D2
SB350
D3
SB350
D4
SB350
R3
10Ω
C3
100nF
R4
10Ω
C4
100nF
Dirty Gnd star
C10
2200µF
35V
C8
2200µF
35V
C12
100nF
R8*
2.26kΩ
C14
22µF
35V
C16
22µF
35V
D8
UF4002
D21
1N4001
Op amp power
R10
120Ω
R12
1Ω
–34V
–34V Unreg
R6
1Ω
2.5W
–33V
Adj
In IC2 Out
LM337
–25V
C5
1nF
C6
1nF
R13
1kΩ
0.5W
C17
10nF
D6
UF4004
*R7/R8 are Vishay MSR25 0.6W

Fig.32. New values for ±25V power supply using LM317/337 regulators. Obtaining a 22-0-22V transformer may be tricky. Cricklewood electronics do a big 80VA one and RS and CPC do smaller ones. Using the more common 25-0-25V type could exceed the 37V input voltage of the regulators and stress the 35V capacitors.

To work effectively this needs an associated decoupling resistor (R27). (On the early PCB shown in Fig.16, this was inadvertently omitted but is present in the ones supplied by *PE*.)

Instrumentation use

Instrumentation normally demands DC precision with low offset. DOAs have high unit-to-unit spreads, especially if they use random unmatched input transistors for TR1 and TR2. If the transistors are closely matched for V_{be} at a low current and reasonably matched for H_{fe}, the DC performance will be adequate. Matching of the current mirror transistors TR4 and TR5 is less critical, but the V_{be} values need to be close. If you don't have access to a transistor analyser you can just put 3-pin sockets in the board and pick out pairs giving the lowest offsets and closest currents. The simplest way to do this is to solder in turned-pin socket strips, as shown in Fig.33.

Mike Grindle (our PCB designer) has positioned the transistor pairs so they are thermally coupled with their flat sides facing each other to reduce drift. He has also provided pads for the dual SMT Toshiba devices (shown in Fig.34). Even untrimmed, these devices will give much better DC performance than separate unmatched transistors.

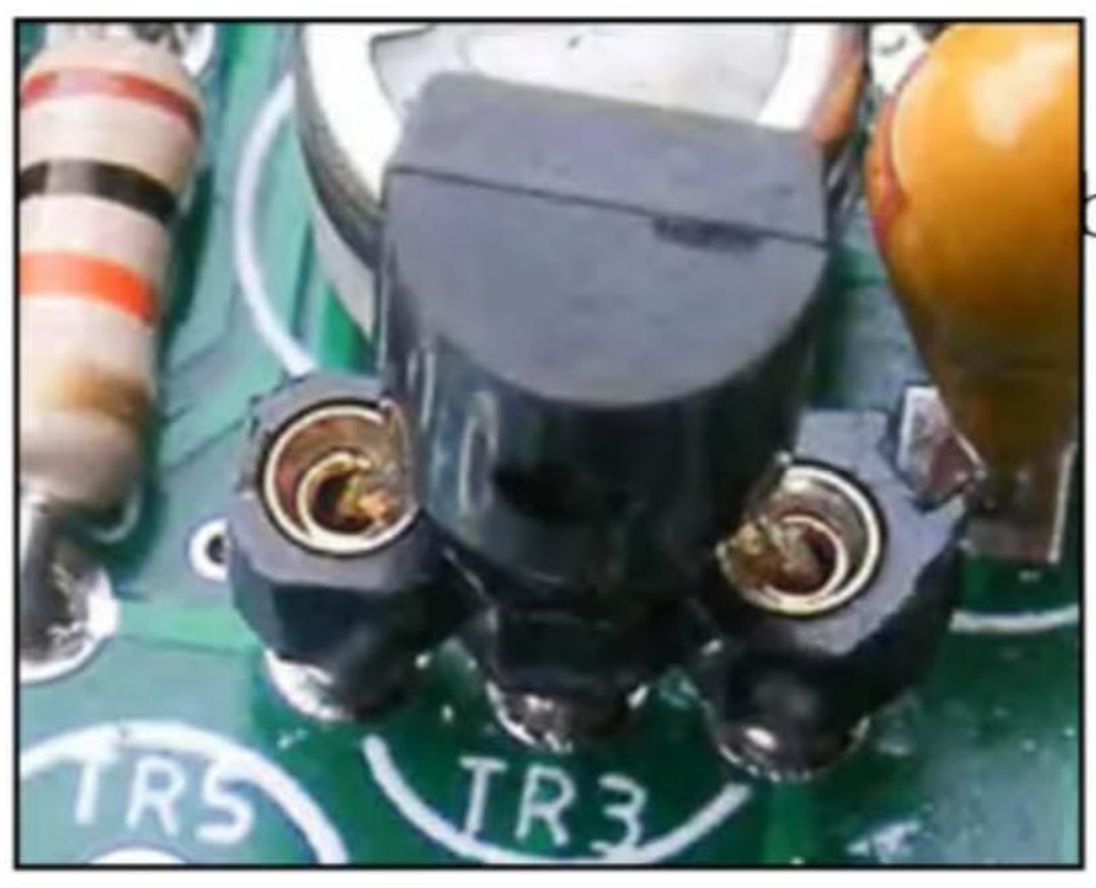


Fig.33. Trying different transistors is easy if you install sockets. In this case I was trying different types for TR3.

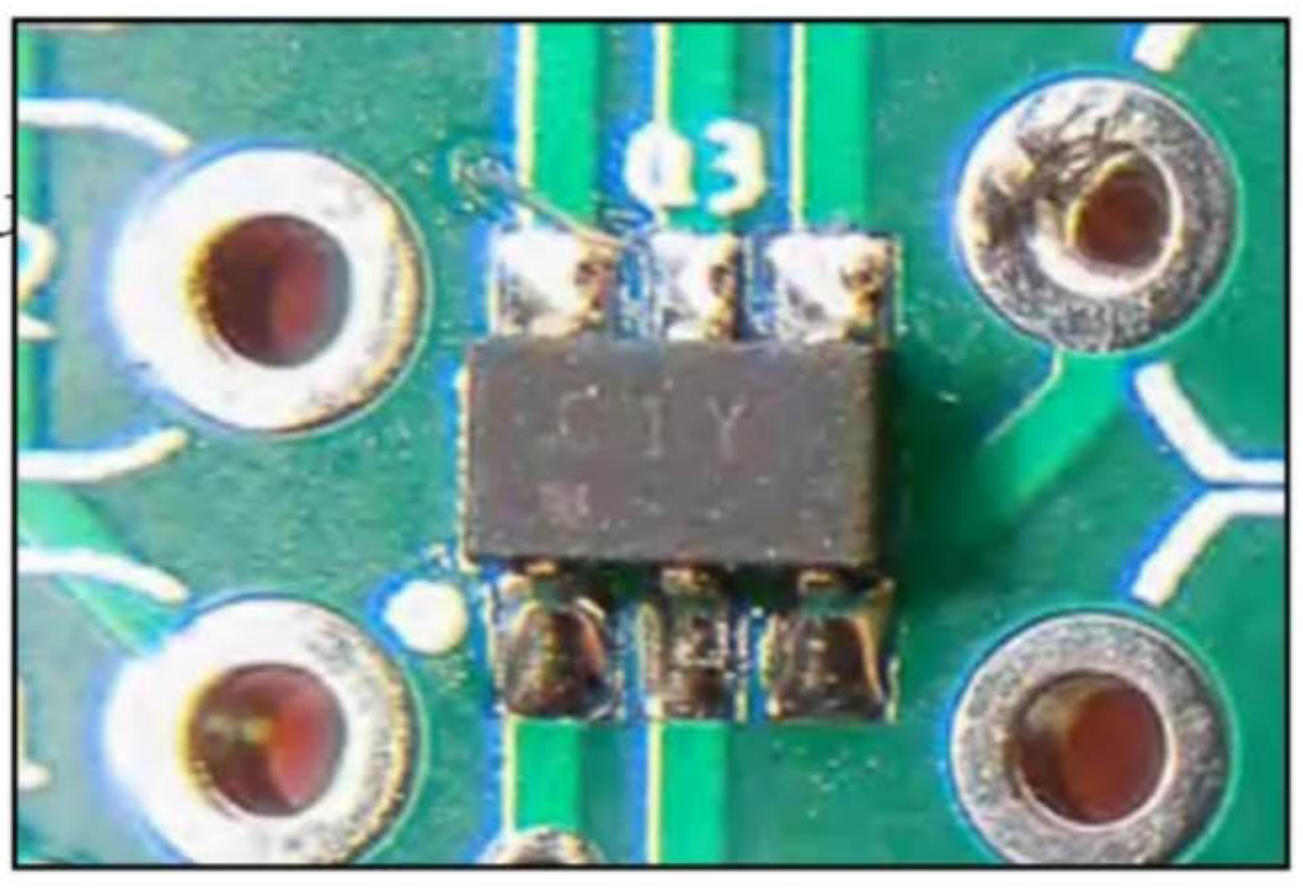
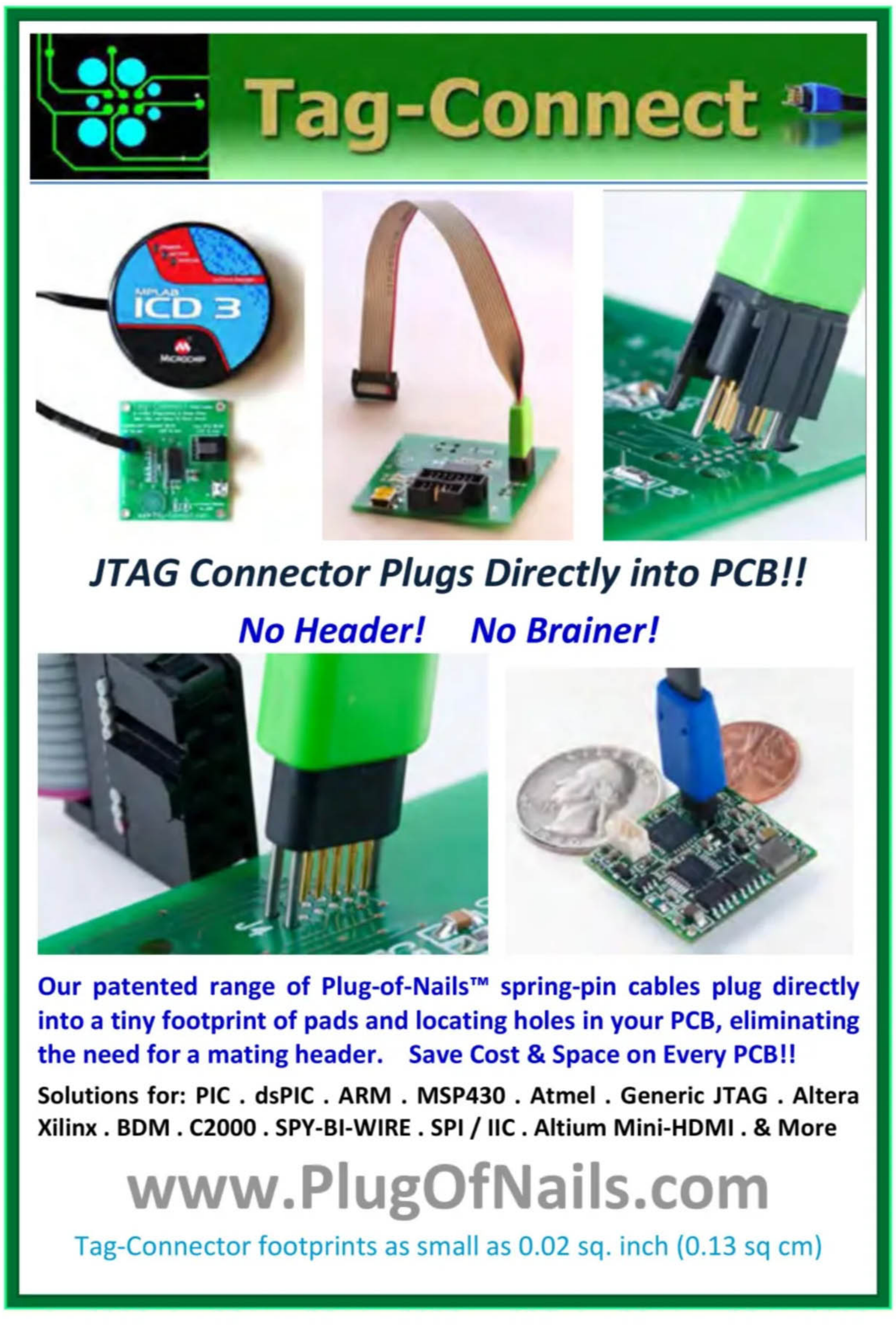


Fig.34. Toshiba dual transistors – note TR1 marking is 'C1Y' (for TR2 it is 'D1G'). Solder these devices first. They can go in either way.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Pocket Theremin (*EPE*, 1996)	**£4.00**
Elysian Theremin (*EPE*, 1996)	**£12**
Synth VCF, VCO (*EPE*, 2017)	**£3.00**
48V PSU (*EPE*, 2019)	**£3.00**
Relays	
STC hermetic 4190 24V DPDT	**£4.00**
Switches Blore Edwards/Plessey	
MH1 4-pole 3-way	**£3.00**
Elma 01 2-pole 6-way	**£6.00**
3PDT guitar pedal stomp switch	**£2.50**
Valves	
EC88, PCL84	**£3.00**
Robert's Radio modules	
Tuners LP1169, LP1179	**£7.00**
IF strip LP1171	**£7.00**
Knobs – large Bakelite	
Bulgin 1960s and Sifam 1970s	**£1.50**

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Jake Rothman
The Old Rectory, Arlais Road,
Llandrindod Wells, Powys
LD1 5HE (visit by appointment)
+44 (0)1597 829102
jrothman1962@gmail.com

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KickStart

by Mike Tooley

Part 13: Using low-cost colour LCD displays with the Raspberry Pi Pico

Our occasional *KickStart* series aims to show readers how to use readily available low-cost components and devices to solve a wide range of common problems in the shortest possible time. Each of the examples and projects can be completed in no more than a couple of hours using 'off-the-shelf' parts. As well as briefly explaining the underlying principles and technology used, the series will provide you with a variety of representative solutions and examples, along with just enough information to be able to adapt and extend them for their own use.

This thirteenth instalment shows you how to add a low-cost colour LCD to your Raspberry Pi Pico microcontroller-based projects. Using IPS and TFT technology, these inexpensive devices can really bring your project to life; providing you with a means of displaying prompts, messages and colour graphics, as well as adding touchscreen buttons that will let you interact with the Pico.

To show you just how easy these modules are to use, we will take you step-by-step through the design and coding of a useful audio application for a microcontroller in the form of an analogue recording level indicator.

A quick trawl through back issues of PE will reveal that simple microcontroller projects can often be built using nothing more than a few sensors and a couple of LED indicators. However, when things get a bit more complex there's a need for a better way of displaying information and, while this can be achieved using a simple 16×2 or 20×4-character alphanumeric display, there's now a range of highly affordable colour LCD modules that offer a much more flexible and attractive solution. Using the appropriate driver software these displays are delightfully easy to use and programming couldn't be simpler. For example, to display a line of yellow text against a red background you would just need to include these statements in your code:

```
LCD.fill(LCD.RED)
LCD.text("CPU TEMPERATURE",6,16,LCD.YELLOW)
```

To display a blue rectangle containing white text you could use:

```
LCD.fill_rect(0,40,160,20,LCD.BLUE)
LCD.text("Pico-LCD-1.8",2,48,LCD.WHITE)
```

Display types and technologies

Two closely related technologies are used in low-cost colour LCD displays. They are TFT (thin-film transistor) and IPS (in-plane switching). Modern, cost-effective TFT displays offer good efficiency coupled with compact dimensions, while more complex IPS displays provide improved colour reproduction coupled with wider viewing angles.

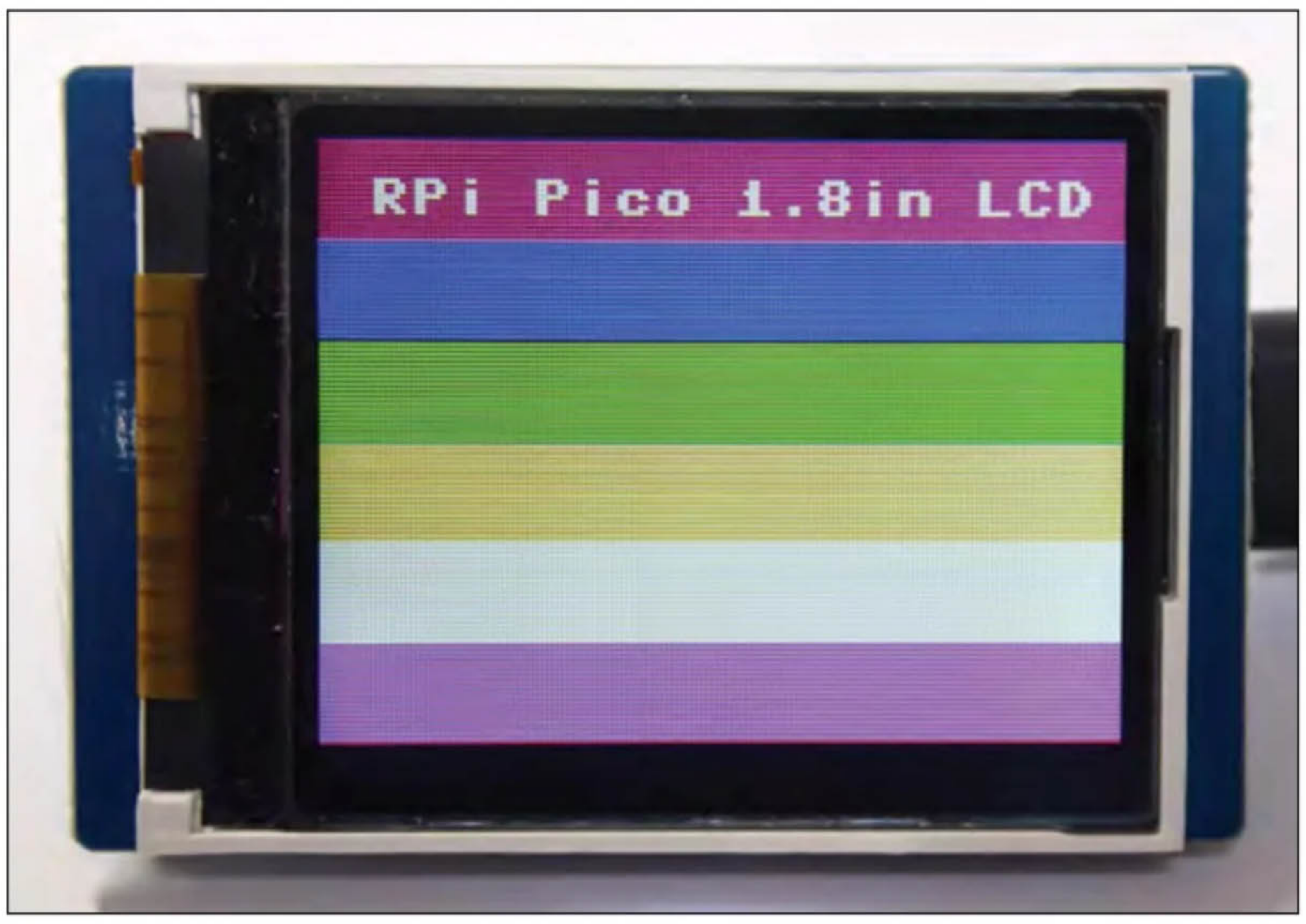


Fig.13.1. Colour bars displayed on the Waveshare 1.8-inch colour LCD.

Unlike OLED displays, TFT and IPS displays are transmissive and thus require a separate back-light source. The intensity (or brightness) of the display can be controlled by setting the duty cycle of the waveform applied to the backlight. This can be a useful feature when a display is to be used in situations where there can be wide variations in ambient light.

Several manufacturers have responded to the need for low-cost TFT displays capable of interfacing with today's popular microcontrollers with the necessary driver and serial peripheral interface (SPI) incorporated into a range of 'backpack' modules. Those currently available from Waveshare (based on TFT and IPS technologies) are summarised in Table 13.1, so you need look no further if you need a colour LCD for use with your Raspberry Pi Pico (RPi Pico).

The colour LCD selected for use in our sample application (see later) is the Waveshare 1.44-inch module. This low-cost display offers the following specification:

- 64K RGB colours
- 128 × 128 pixels (0.2mm pixel size)
- SPI four-wire microcontroller host interface
- Interconnection compatibility with the RPi Pico via an on-board female pin header.
- Embedded ST7735S display driver

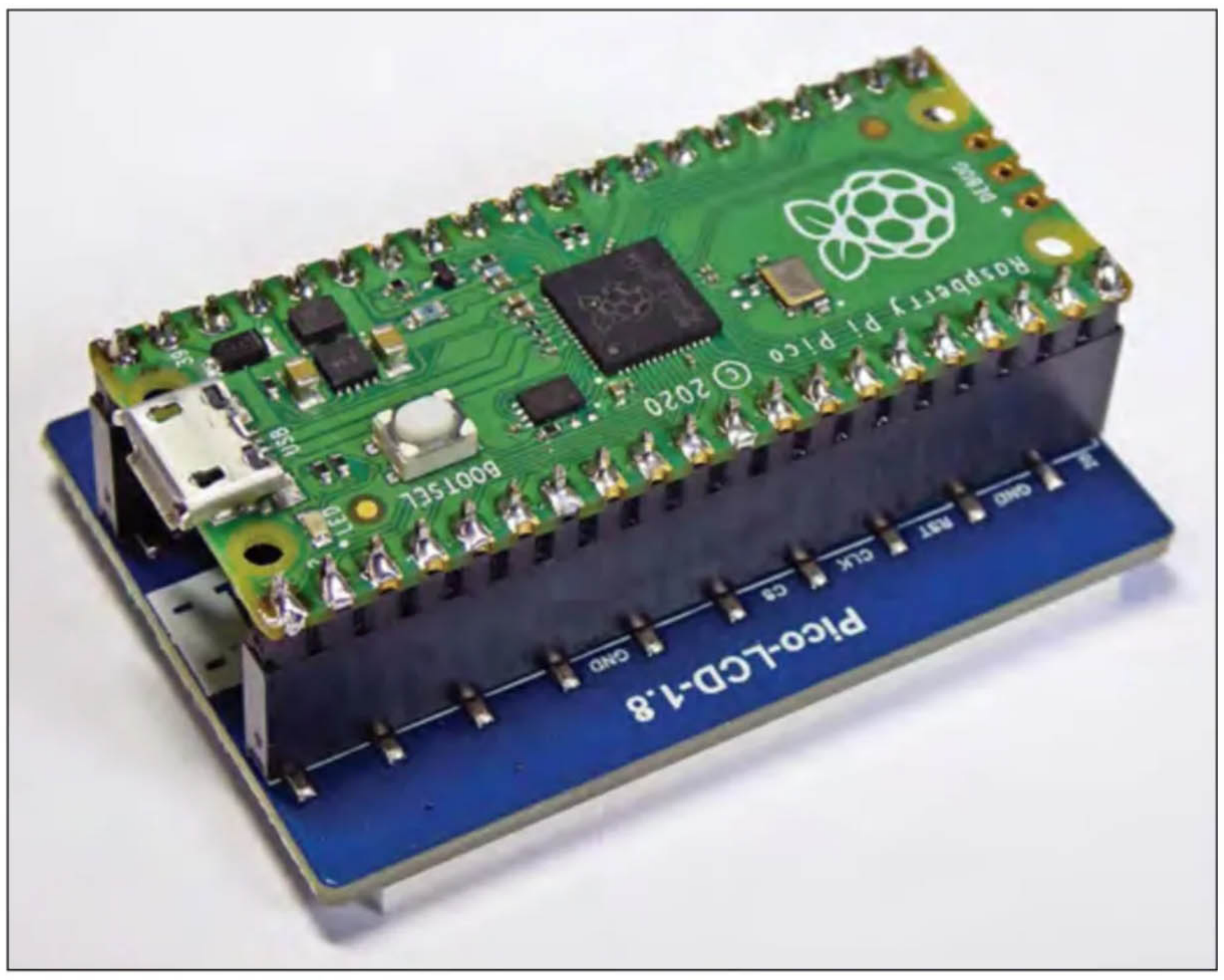


Fig.13.2. The 1.8-inch colour LCD module attaches neatly to the rear of the RPi Pico.

Table 13.1 Waveshare low-cost colour LCD modules

Display	Type	Colours	Pixels	Dimensions	Interface	Driver	Board size (mm)
Pico-LCD-0.96	IPS	65K	160×80	21.70×10.80	SPI	ST7735S	52.00×25.00
Pico-LCD-1.14	IPS	65K	240×135	24.91×14.86	SPI	ST7789	52.00×25.00
Pico-LCD-1.3	IPS	65K	240×240	23.40×23.40	SPI	ST7789	52.00×26.50
Pico-LCD-1.44	**TFT**	**65K**	**128×128**	**25.50×26.50**	**SPI**	**ST7735S**	**52.00×26.50**
Pico-LCD-1.8	TFT	65K	160×128	35.04×28.03	SPI	ST7735S	52.00×34.50
Pico-LCD-2	IPS	65K	320×240	40.80×30.60	SPI	ST7789VW	52.00×35.00
Pico-ResTouch-LCD-2.8	IPS	262K	320×240	57.60×43.20	SPI	ST7789	70.20×50.20
Pico-ResTouch-LCD-3.5	IPS	65K	480×320	73.44×48.96	SPI	ILI9488	86.00×57.20

- Operating voltage over the range 3.15V to 5V
- Overall dimensions 52.0 × 30.0mm
- C/C++ and MicroPython development resources
- Four configurable buttons for user input.

Connecting to the RPi Pico

The 1.44-inch Waveshare LCD modules require connection to the Pico's supply as well as a subset of its I/O lines. The 1.44-inch module needs to access the following Pico pins: GP8 to GP13 for SPI (see Fig.13.3) together with GP2, GP3, GP15 and GP17 if you wish to make use of the four user-definable button keys. This still leaves plenty of connectivity available for other external hardware (all unmarked pins shown on Fg.13.3 remain available for use.

Table 13.2 summarises the required connections and corresponding signal functions for the 1.44-inch module. Note that these connections are all made for you when the backpack module is attached to the Pico. Thus, if you've already fitted headers to your RPi Pico then there's no need for any additional soldering or wiring.

Using colour

Before we launch into the subject of colour handling, it is important to be aware that display data is assembled and held in a memory buffer before it is sent to the LCD. Each time the display needs updating the relevant commands *must* be followed by `lcd.show()`. If you fail to include `lcd.show()` in your code nothing new will appear on screen. This is an important point which can be easily forgotten.

In your code, colour can be expressed in various ways, but for most purposes a 16-bit hexadecimal value is convenient. For example, the display background colour can be set using the `LCD.fill()` command. This command accepts a single parameter used to determine the background colour. The colour parameter is a 16-bit value with hexadecimal values in the range 0000 to FFFF. As an example, `LCD.fill(0x0000)` (or simply `LCD.fill(0)`) is used to set a white background whereas `LCD.fill(0xFFFF)` is used to set a black background.

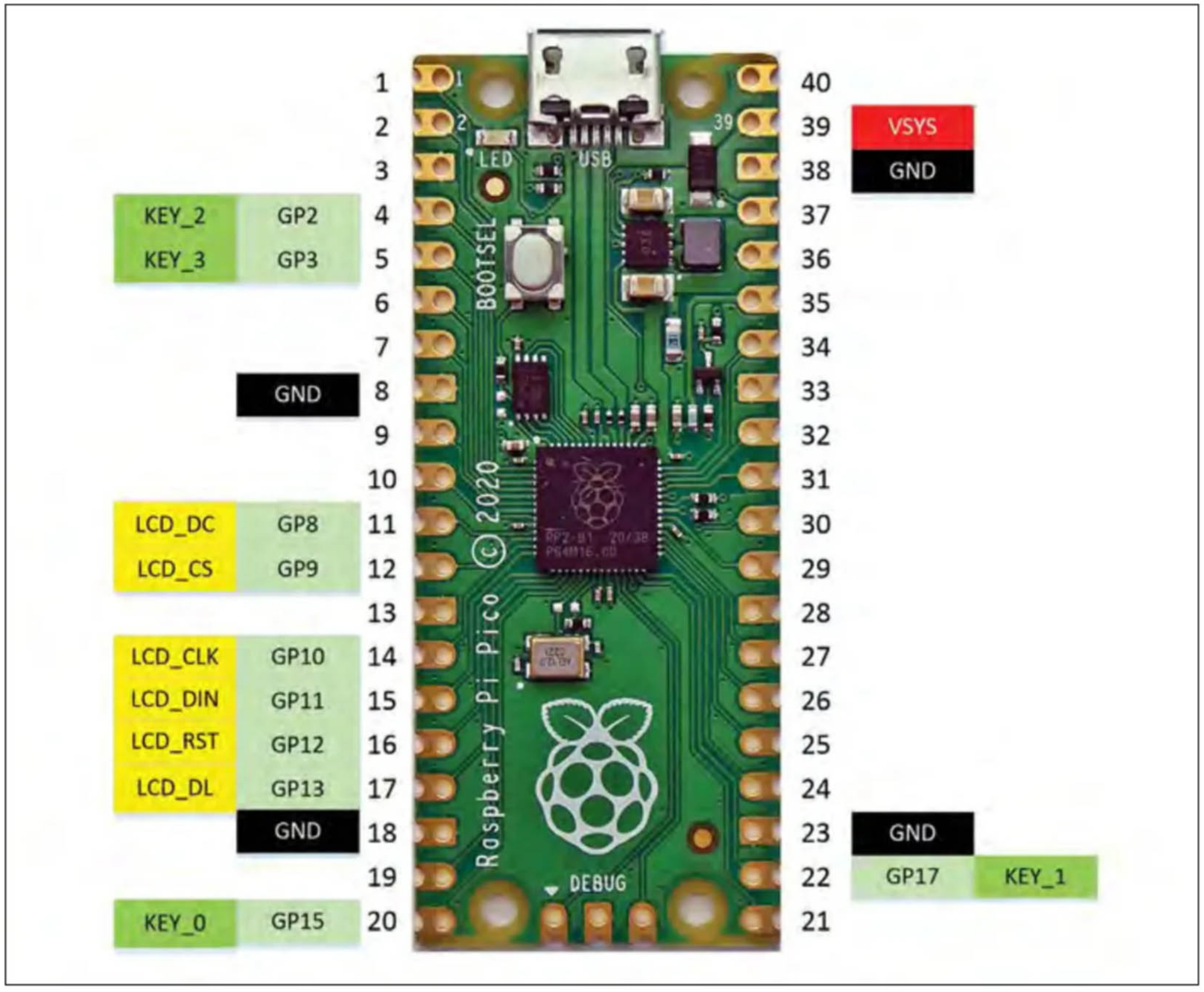


Fig.13.3. Pico pins required for the Waveshare 1.44-inch colour LCD module.

Unfortunately, using hexadecimal values to specify red, green and blue (RGB) colour intensities can sometimes be a little tricky. The Waveshare modules use a clever coding scheme designed to reduce memory overhead. In this scheme, three-byte colour values (24-bits per pixel) are reduced to two-bytes (16-bits) thus reducing the memory overhead by 33%. Since the human eye is more sensitive to green light than other colours of the spectrum (red and blue) we can use six of the available 16-bits to represent green and five of the remaining bits to represent each of the remaining colours (red and blue). Thus 64 possible levels of green are possible and 32 levels for both red and blue.

Table 13.2 Wiring to the RPi Pico for a Waveshare 1.44-inch LCD module

RPi Pico	LCD	Function
VSYS	VSYS	Power supply (3.15 to 5V)
GND	GND	Ground/0V
GP2	KEY_2	User key 2
GP3	KEY_3	User key 3
GP8	LCD_DC	Data/command (high for data, low for command)
GP9	LCD_CS	Chip select (active low)
GP10	LCD_CLK	SPI clock
GP11	LCD_DIN	SPI data
GP12	LCD_RST	Reset (active low)
GP13	LCD_BL	LCD backlight
GP15	KEY_0	User key 0
GP17	KEY_1	User key 1

Do note that the RGB colour data used for each pixel in the display is stored in a way that might not seem very logical

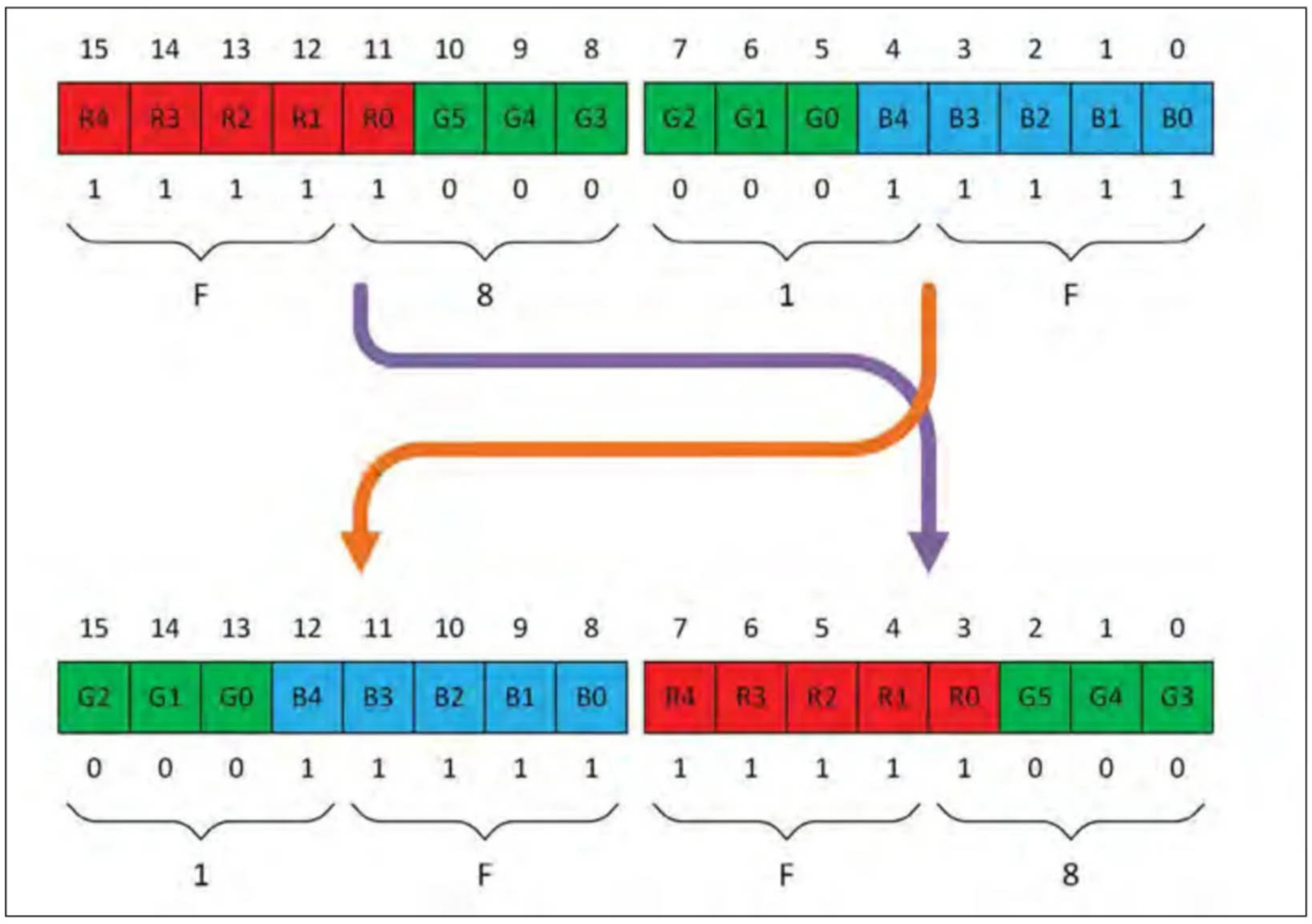

15 14 13 12 11 10 9 8 7 6 5 4 3 2 1 0
R4 R3 R2 R1 R0 G5 G4 G3 G2 G1 G0 B4 B3 B2 B1 B0
1 1 1 1 1 0 0 0 0 0 0 1 1 1 1 1
F 8 1 F
15 14 13 12 11 10 9 8 7 6 5 4 3 2 1 0
G2 G1 G0 B4 B3 B2 B1 B0 R4 R3 R2 R1 R0 G5 G4 G3
0 0 0 1 1 1 1 1 1 1 1 1 1 0 0 0
1 F F 8

Fig.13.4. Two different ways of storing the same RGB colours.

at first sight. This is compounded by the fact that different displays may exhibit different coding schemes compared to the 1.44-inch and 1.8-inch modules used here. Their colour data may be in a different sequence, thus necessitating a different set of colour values to represent identical colours on two different modules. Figs.13.4 and 13.5 illustrate this anomaly. Providing you pay attention to this you will be fine – just do be aware that colour coding is not a 'one-size fits all'.

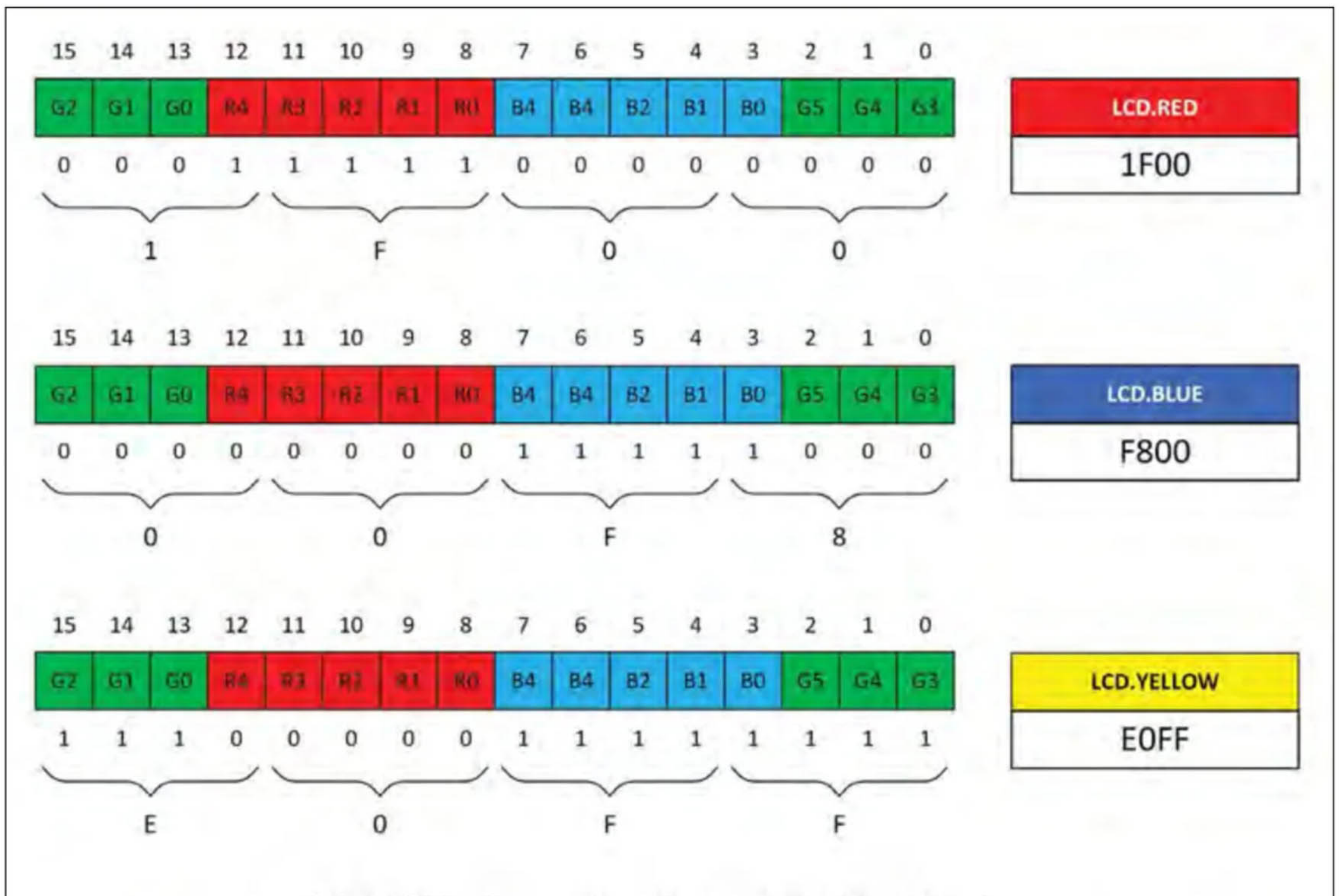
Naming the colours

Although low-cost TFT displays can display a huge range of colours, a smaller range is perfectly adequate for most applications and rather than having to remember hexadecimal values it's useful to refer to those most frequently used by name. The following code fragment defines the author's 16 preferred colours for use with the Waveshare 1.44-inch LCD display module, but the names/values that you use for your own colours is entirely up to you.

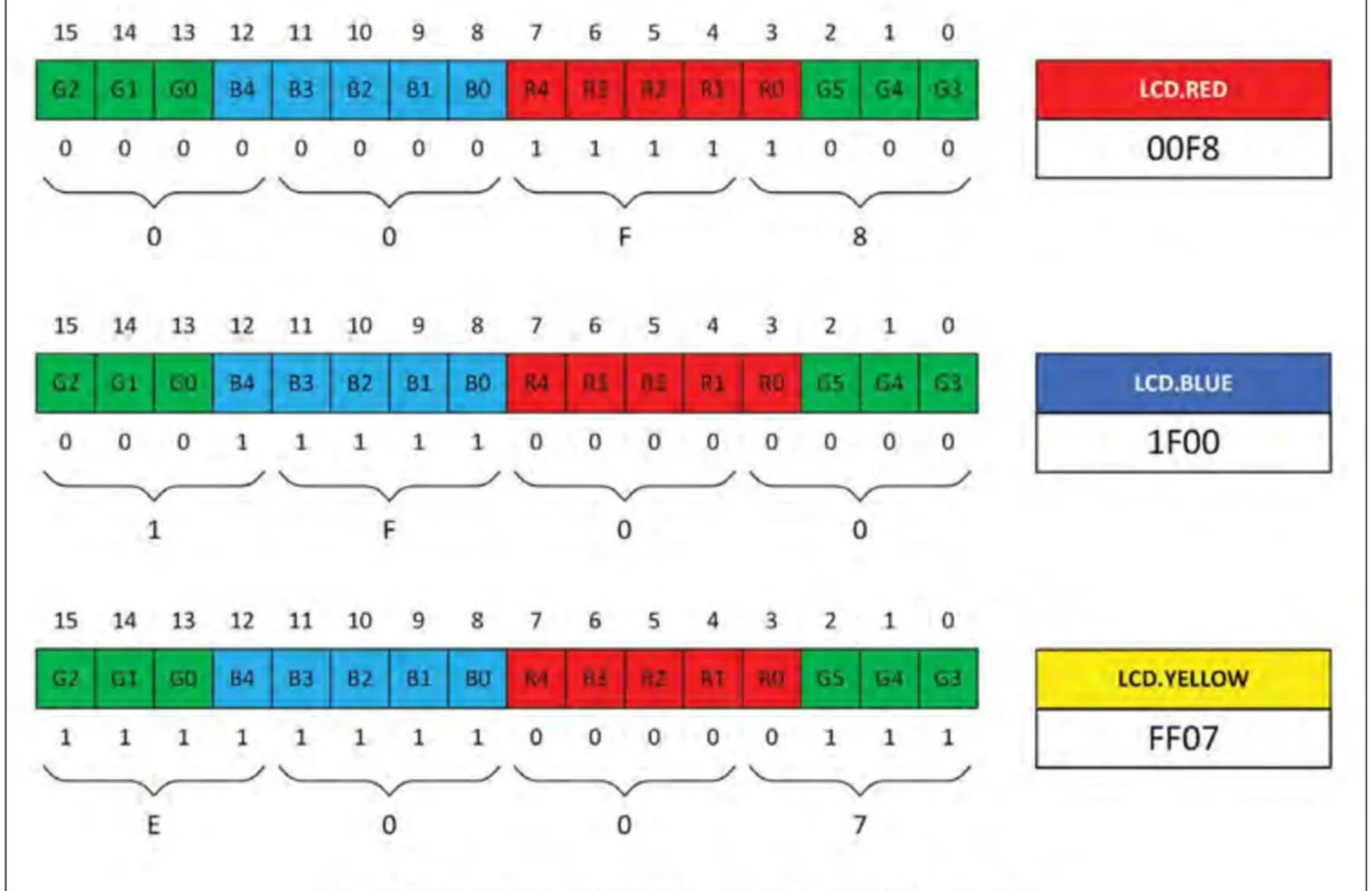
```
# Define 16 colour values
for the 1.44-inch LCD module
self.CYAN    = 0xE0FF
self.BLACK   = 0x0000
self.BLUE    = 0x00F8
self.MAGENTA = 0x1FF8
self.GREY    = 0x1084
self.GREEN   = 0x0004
self.LIME    = 0xE007
self.MAROON  = 0x1000
self.NAVY    = 0x0080
self.OLIVE   = 0x1004
self.PURPLE  = 0x1080
self.RED     = 0x1F00
self.SILVER  = 0x18C6
self.TEAL    = 0x0084
self.WHITE   = 0xFFFF
self.YELLOW  = 0xFF07
```

Other ways to express colour data

It's useful to have some means of converting colour data from one format to another. 24-bit colour data (occupying three bytes) is often referred to as RGB888 because 8-bits are used to represent each of the three colours. Instead of using 24-bit hexadecimal values it can sometimes be handy to employ decimal numbers (referred to as RGB dec.). The


15 14 13 12 11 10 9 8 7 6 5 4 3 2 1 0
G2 G1 G0 R4 R3 R2 R1 R0 B4 B4 B2 B1 B0 G5 G4 G3
0 0 0 1 1 1 1 1 0 0 0 0 0 0 0 0
1 F 0 0
LCD.RED
1F00
15 14 13 12 11 10 9 8 7 6 5 4 3 2 1 0
G2 G1 G0 R4 R3 R2 R1 R0 B4 B4 B2 B1 B0 G5 G4 G3
0 0 0 0 0 0 0 0 1 1 1 1 1 0 0 0
0 0 F 8
LCD.BLUE
F800
15 14 13 12 11 10 9 8 7 6 5 4 3 2 1 0
G2 G1 G0 R4 R3 R2 R1 R0 B4 B4 B2 B1 B0 G5 G4 G3
1 1 1 0 0 0 0 0 1 1 1 1 1 1 1 1
E 0 F F
LCD.YELLOW
E0FF

(a) 16-bit colour values for the 1.44" LCD display


15 14 13 12 11 10 9 8 7 6 5 4 3 2 1 0
G2 G1 G0 B4 B3 B2 B1 B0 R4 R3 R2 R1 R0 G5 G4 G3
0 0 0 0 0 0 0 0 1 1 1 1 1 0 0 0
0 0 F 8
LCD.RED
00F8
15 14 13 12 11 10 9 8 7 6 5 4 3 2 1 0
G2 G1 G0 B4 B3 B2 B1 B0 R4 R3 R2 R1 R0 G5 G4 G3
0 0 0 1 1 1 1 1 0 0 0 0 0 0 0 0
1 F 0 0
LCD.BLUE
1F00
15 14 13 12 11 10 9 8 7 6 5 4 3 2 1 0
G2 G1 G0 B4 B3 B2 B1 B0 R4 R3 R2 R1 R0 G5 G4 G3
1 1 1 1 1 1 1 1 0 0 0 0 0 1 1 1
E 0 0 7
LCD.YELLOW
FF07

(b) 16-bit colour values for the 1.8" LCD display

Fig.13.5. Format of the 16-bit colour data used for the 1.44-inch and 1.8-inch Waveshare LCD modules (note the different hexadecimal values used for identical colours).

16-bit representation (with just two bytes mentioned earlier) is referred to a RGB565. Table 13.3 shows how 16 of the most commonly used colours can be expressed in different formats.

Converting RGB colour values

To help with the conversion of RGB dec colours to RGB565 hex colours we've provided some simple Python utilities for both the 1.44-inch and 1.8-inch displays. These can be downloaded from the *PE* website (see *Going further*). These utilities are simple to use but an example might help. Let's assume that you need to display a gold colour (corresponding to 255, 202, 0 in RGB888 dec) on the Waveshare 1.44-inch module. If you enter these values into our colour code application, you will find that the required RGB565 hex data is 5F06. You could then define this new colour as:

`LCD.GOLD = 0x5F06`

Alternatively, just include it earlier in the driver's list of colour definitions as:

`self.GOLD = 0x5F06`

It really is that simple.

Controlling the display intensity

As briefly mentioned earlier, the intensity or brightness of the display can be adjusted by varying the duty cycle of the pulse-width modulated (PWM) signal applied to the display. This is achieved by means of the `pwm.duty_u16()` command. The parameter passed by this command can take any value between 0 and 65535 (or 0xFFFF in hexadecimal), with the largest value corresponding to maximum brightness. Listing 1 shows how the intensity of a display can be reduced from maximum to zero and vice versa.

The code assumes that you have imported the required libraries (`Pin` and `utime`) and that the colour definitions for `LCD.RED` and `LCD.CYAN` have been included in your driver code (see *Going further*).

Display layout

Before you attempt to design a layout for your LCD it is important to be aware of the parameters that you will be working with. Taking the 1.44-inch LCD as an example, this comprises a 128×128 matrix of individual pixel elements. Individual pixels can be identified by referring to their column (x-axis) and row (y-axis) position. Thus, the

Table 13.3 Comparison of colour values

Colour (Note 1)	RGB888 hex (24-bit)	RGB dec (24-bit)	RGB565 hex (16-bit) (Note 1)	LCD colour name (Note 2)
Aqua	0x00FFFF	0,255,255	0xFF07	LCD.AQUA
Black	0x000000	0,0,0	0x0000	LCD.BLACK
Blue	0x0000FF	0,0,255	0x1F00	LCD.BLUE
Fuchsia	0xFF00FF	255,0,255	0x1FF8	LCD.FUCHSIA
Gray	0x808080	128,0,128	0x0F78	LCD.GRAY
Green	0x008000	0,128,0	0xE003	LCD.GREEN
Lime	0x00FF00	0,255,0	0xE007	LCD.LIME
Maroon	0x800000	128,0,0	0x0078	LCD.MAROON
Navy	0x000080	0,0,128	0x0F00	LCD.NAVY
Olive	0x808000	128,128,0	0xE07B	LCD.OLIVE
Purple	0x800080	128,0,128	0x0F78	LCD.PURPLE
Red	0xFF0000	255,0,0	0x00F8	LCD.RED
Silver	0xC0C0C0	192,192,192	0xF7BD	LCD.SILVER
Teal	0x008080	0,128,128	0xEF03	LCD.TEAL
White	0xFFFFFF	255,255,255	0xFFFF	LCD.WHITE
Yellow	0xFFFF00	255,255,0	0x1FF8	LCD.YELLOW

Notes: 1. Values are shown for the Waveshare 1.8-inch LCD module
2. Colour names can vary.

Listing 13.1. Fading the display

```
# Fade the display
LCD.fill(LCD.RED)          # Red background
LCD.text("Fading >>>>",16,48,LCD.WHITE)
pwm = PWM(Pin(BL))
pwm.freq(1000)
intensity = 0xFFFF         # Start with maximum brightness
for i in range(16):        # Fade out
pwm.duty_u16(intensity)
intensity -= 0x0FFF
LCD.show()
utime.sleep(0.25)
for i in range(16):        # Fade in
pwm.duty_u16(intensity)
intensity += 0x0FFF
LCD.show()
utime.sleep(0.25)

# Finished notification
pwm.duty_u16(0xFFFF)
LCD.fill(LCD.BLACK)
LCD.text("Finished!",24,48,LCD.WHITE)
LCD.show()
```

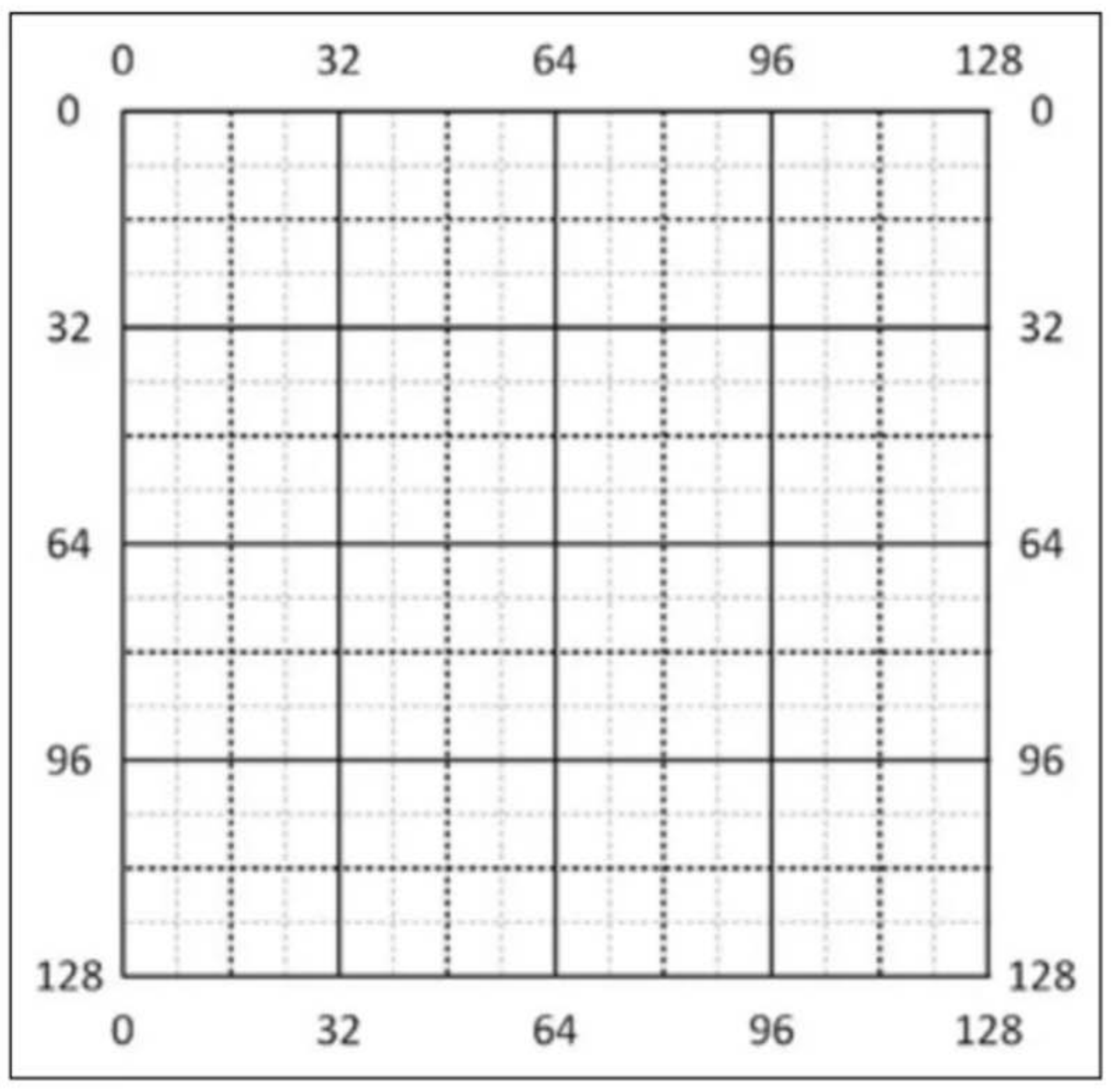


Fig.13.6. (left) Screen template for the 1.44-inch colour LCD.

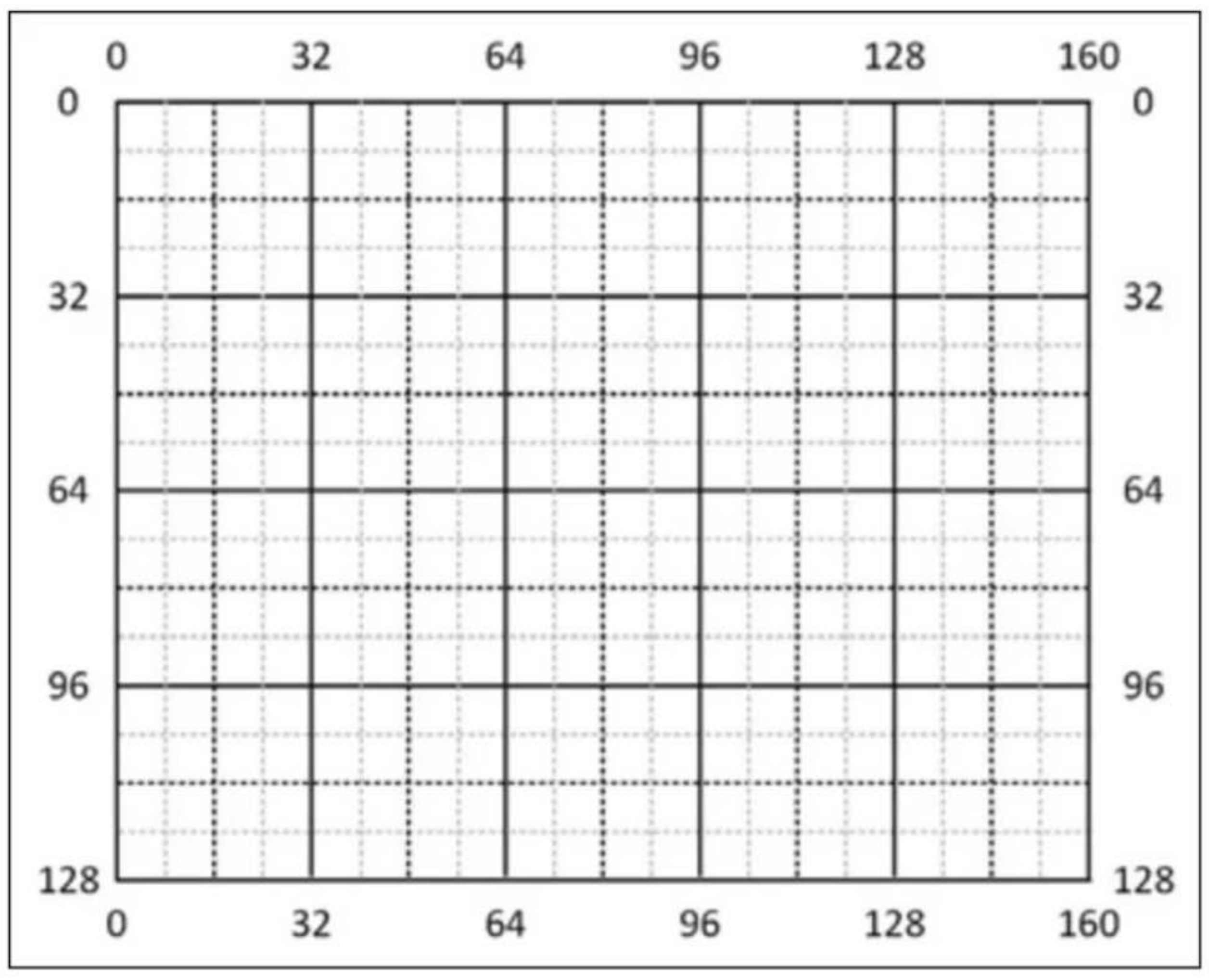


Fig.13.7. (right) Screen template for the 1.8-inch colour LCD.

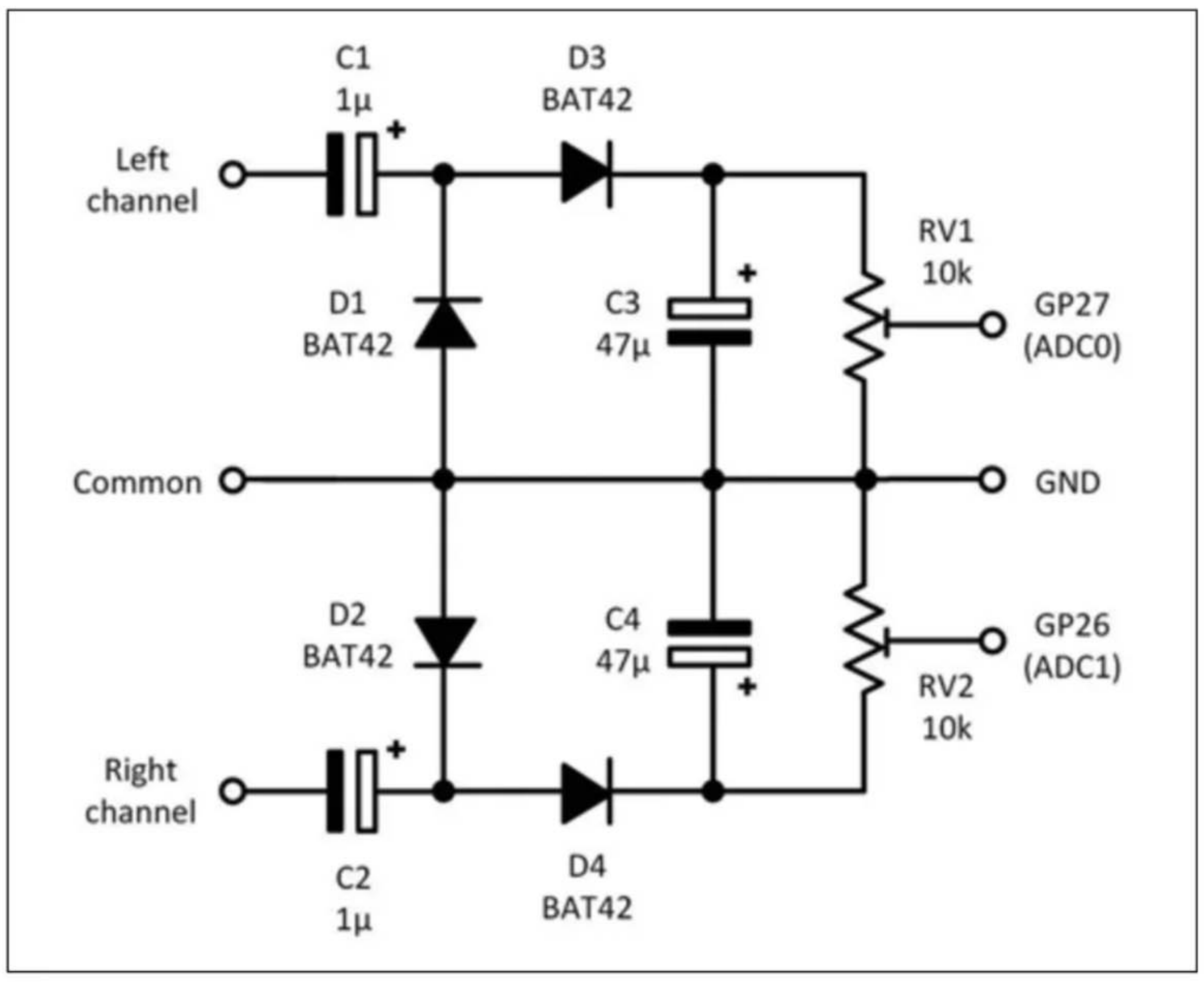

C1
1µ
D3
BAT42
Left channel
D1
BAT42
C3
47µ
RV1
10k
GP27 (ADC0)
Common
GND
D2
BAT42
C4
47µ
GP26 (ADC1)
RV2
10k
Right channel
C2
1µ
D4
BAT42

Fig.13.10. Circuit of the signal level detector.

coordinates of the pixel at the top left of the screen (column 0, row 0) are (0,0) and to set this pixel to white (0xFFFF) you could use:

```
LCD.pixel(0,0,0xFFFF) # Top left corner pixel
to white
```

Similarly, to set the pixel at the exact centre (64,64) of the 1.44-inch LCD to black you could use:

```
LCD.pixel(64,64,0x0000)  # Centre
pixel to black
```

Since the 1.44-inch display uses 128×128 pixels the total number of pixels available is 16,384. With two bytes of colour data allocated to each pixel the memory required for storing screen data will thus be 32,768 bytes. To assist you with your own screen layouts we've provided templates for the 1.44-inch and 1.8-inch LCD. We've also made these available as a PDF so that you can download and print them (see *Going further*).

Displaying text

The low-cost LCD modules use an 8×8 font so each character displayed requires 64 pixels. With a 1.44-inch LCD up to 16 characters can appear in a single line of text, but with a 1.8-inch module this increases to a maximum of 20 characters. For example, to display 'Hello Pico World' in white text starting at the top left corner of the screen (0,0) you could use:

```
LCD.text("Hello Pico World",0,0,
LCD.WHITE)
```

These 16 characters will exactly fill the top line of a 1.44-inch display. Notice in this example that we've used a colour value that we've previously defined (`LCD.WHITE`) but instead we could have used:

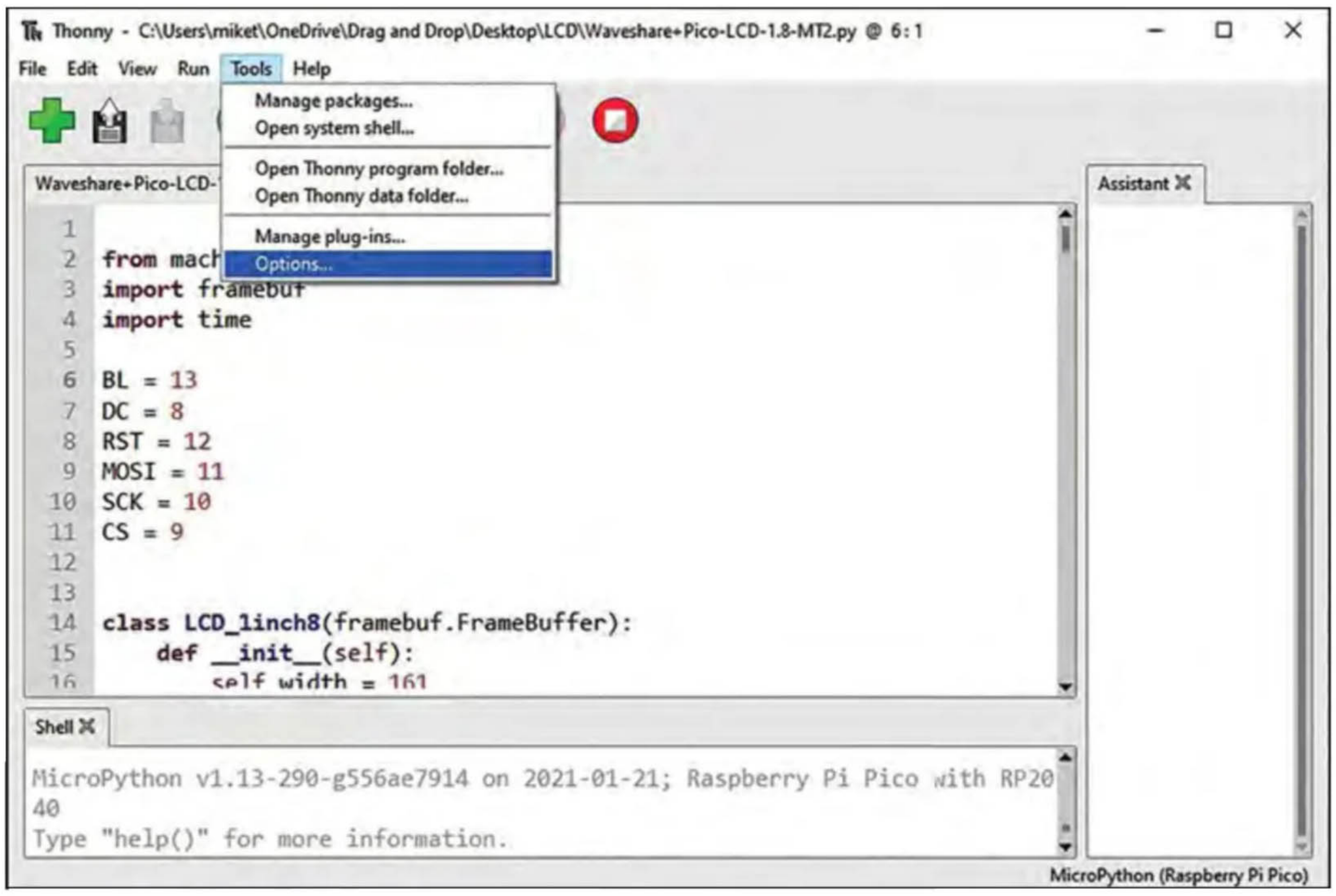
```
LCD.text("Hello  Pico  World",0,0,
0xFFFF)
```

Scrolling your text

Text can easily be made to scroll across the display – see Listing 2.

Listing 13.2. Scrolling text

```
# Scroll a message
def scroll(my_string,xpos,ypos,colour):
   x = 0
   while x < len(my_string):
        char = my_string[x]
        LCD.text((my_string)[x],xpos,ypos,colour)
        LCD.show()
        utime.sleep(0.2)
        x += 1
        xpos = xpos + 8

# Scroll wait message
x = 0
xpos = 0
ypos = 16
scroll("Please wait >>>",8,48,LCD.WHITE)
utime.sleep(4)
# Finished notification
pwm.duty_u16(0xFFFF)
LCD.fill(LCD.BLACK)
LCD.text("Finished!",24,48,LCD.WHITE)
LCD.show()
```

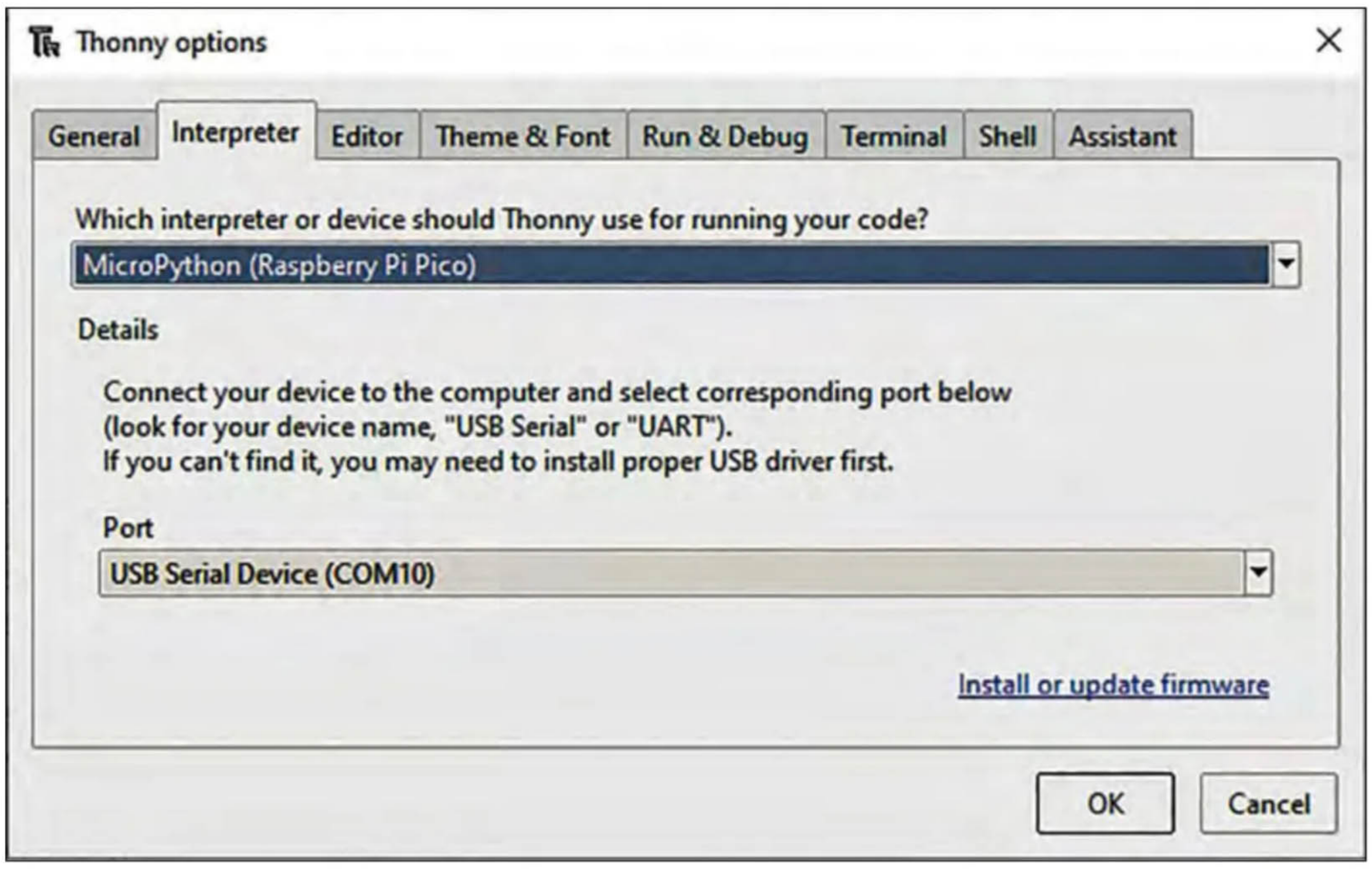

File
Edit
View
Run
Tools
Help
Manage packages...
Open system shell...
Open Thonny program folder...
Open Thonny data folder...
Manage plug-ins...
Options...
Waveshare+Pico-LCD-
Assistant
Shell
MicroPython (Raspberry Pi Pico)

Thonny - C:\Users\miket\OneDrive\Drag and Drop\Desktop\LCD\Waveshare+Pico-LCD-1.8-MT2.py @ 6 : 1

```

from mach
import framebuf
import time

BL = 13
DC = 8
RST = 12
MOSI = 11
SCK = 10
CS = 9


class LCD_1inch8(framebuf.FrameBuffer):
    def __init__(self):
        self width = 161
```

```
MicroPython v1.13-290-g556ae7914 on 2021-01-21; Raspberry Pi Pico with RP20
40
Type "help()" for more information.
```

Fig.13.8. Selecting Thonny's Options sub-menu from the main menu bar.


Thonny options
General
Interpreter
Editor
Theme & Font
Run & Debug
Terminal
Shell
Assistant
Install or update firmware
OK
Cancel

Which interpreter or device should Thonny use for running your code?

MicroPython (Raspberry Pi Pico)

Details

Connect your device to the computer and select corresponding port below (look for your device name, "USB Serial" or "UART").
If you can't find it, you may need to install proper USB driver first.

Port

USB Serial Device (COM10)

Fig.13.9. Interpreter and USB port selection.

Lines and rectangles

Lines and rectangles can be easily created, as in the following examples:

1. Draw a 1-pixel yellow line from (32,32) to (64,96)

```
LCD.line(32,32,64,96,LCD.YELLOW)
```

2. Draw a red rectangle starting at (16,16) with a width of 96 and a height of 16 pixels

```
LCD.rect(16,16,96,16,LCD.RED)
```

3. Draw a green-filled rectangle starting at (0,48) with a width of 112 and a height of 16 pixels

```
LCD.fill_rect(0,48,112,16,LCD.GREEN)
```

Further examples (appropriately commented) can be downloaded from the *PE* website (see *Going further*).

User keys

The Waveshare 1.44-inch display has the added bonus of providing you with four key buttons that can be given user-defined functions. These buttons (`key0` to `key3`) are accessible from GP2, GP3, GP15 and GP17 and the keys can be defined using code along the following lines:

```
# Set up buttons
key0 = Pin(15,Pin.IN,Pin.PULL_UP)
key1 = Pin(17,Pin.IN,Pin.PULL_UP)
key2 = Pin(2 ,Pin.IN,Pin.PULL_UP)
key3 = Pin(3 ,Pin.IN,Pin.PULL_UP)
```

Notice that the four key buttons are active in the low state and have thus been given pull-up resistors using `Pin.PULL_UP`. Once defined, the state of the four keys can be interrogated.

Listing 3 is a complete example of how to perform some typical key functions with the results displayed on the LCD. It is available for download from the *PE* website (see *Going further*).

Listing 3. Temperature indicator

```
# Set up the analogue input and temperature sensor channels
analog_input = machine.ADC(26)  # Pico's GP26 is mapped to ADC0
sensor_temp = machine.ADC(4)    # Pico's temperature sensor
start = utime.ticks_ms()

def handle_key1():
    # Read data from the analogue input
    data = analog_input.read_u16()
    # Convert the data to voltage
    # and display the result
    LCD.fill(LCD.BLUE)
    LCD.text("ANALOGUE INPUT",6,16,LCD.YELLOW)
    LCD.text("ADC(0)",40,32,LCD.YELLOW)
    LCD.line(0,56,127,56,LCD.YELLOW)
    LCD.text(str(convert_voltage(data)) + " V",20,64,LCD.WHITE)
    LCD.line(0,80,127,80,LCD.YELLOW)
    LCD.show()
    utime.sleep(2)
    LCD.fill(0)

def handle_key2():
    now = utime.ticks_ms()
    elapsed = utime.ticks_diff(now, start)
    LCD.fill(LCD.NAVY)
    LCD.text("ELAPSED TIME",18,16,LCD.YELLOW)
    LCD.line(0,56,127,56,LCD.YELLOW)
    LCD.text(str(elapsed) + " ms",32,64,LCD.WHITE)
    LCD.line(0,80,127,80,LCD.YELLOW)
    LCD.show()
    utime.sleep(2)
    LCD.fill(0)

def handle_key3():
    LCD.fill_rect(0,0,16,128,LCD.RED)
    LCD.fill_rect(16,0,32,128,LCD.BLUE)
    LCD.fill_rect(32,0,48,128,LCD.LIME)
    LCD.fill_rect(48,0,64,128,LCD.YELLOW)
    LCD.fill_rect(64,0,80,128,LCD.CYAN)
    LCD.fill_rect(80,0,96,128,LCD.MAGENTA)
    LCD.fill_rect(96,0,112,128,LCD.MAROON)
    LCD.fill_rect(112,0,128,128,LCD.PURPLE)
    LCD.show()
    utime.sleep(2)
    LCD.fill(0)

def get_temperature():
    reading = sensor_temp.read_u16() * 0.0000504
    temperature = 27 - (reading - 0.706)/0.001721
    temperature = round(temperature, 2)
    return temperature

def convert_voltage(data):
    voltage = (data - 336) * (3.3 / 65198)
    return voltage
```

A recording level indicator using the RPi Pico

To conclude and to put this month's *KickStart* into context, we will show you how a humble RPi Pico can be used with a 1.44-inch colour LCD module and be used to as an analogue recording level indicator. Traditionally, this task would have required dual moving coil meters, one for the left and one for the right channel. However, a colour LCD is well suited to the task because its appearance and behaviour can be easily customised using just a few lines of code.

If you don't already have a coding environment installed, you will need to get hold of a copy of Thonny (see *Going further*). Instructions for installing and running Thonny with the RPI Pico appeared in *PE* for May 2022 (see *Going further*). Simply connect the USB cable and then select Tools and Options from the Thonny's menu bar (see Fig.13.8). Next, select the RPi Pico interpreter and the appropriate USB port (see Fig.13.9). It's best to start with some of the sample code that we've provided from the *PE* website (see *Going further*). Transfer the code to the directory of your choice, open it in Thonny and then click on the 'Run' icon (the green circled arrow).

The recording level indicator uses two of the Pico's analogue channels, ADC0 and ADC1. These need to be fed with the outputs of a simple detector arrangement which converts a low-level audio signal to a peak DC level (see Fig.13.10). The components can be assembled using a small piece of stripboard. Layout and wiring are not especially critical, but unless the audio inputs are kept reasonably short then it

Listing 4. Recording level indicator

```
# Recording level indicator
LCD.fill(0)                 # Clear the LCD to black
LCD.show()
scale = 184                 # Scale factor for adjusting signal level
delay = 0.1                 # 100 ms delay between readings
while True:
# Left and right pointer positions
   left_input = machine.ADC(26)  # Pico's GPIO GP26 is mapped to ADC0
   right_input = machine.ADC(27) # Pico's GPIO GP27 is mapped to ADC1
   left_data = left_input.read_u16()
   right_data = right_input.read_u16()
   lpos = int(left_data / scale)     # Convert float to int
   rpos = int(right_data / scale)
# Meter legend
   LCD.text("RECORD LEVEL",16,8,LCD.CYAN)
   LCD.line(16,18,112,18,LCD.CYAN)
   LCD.text("Left",0,40,LCD.CYAN)
   LCD.text("Right",0,72,LCD.CYAN)
   LCD.text("0dB",88,40,LCD.OLIVE)
   LCD.text("0dB",88,72,LCD.OLIVE)
# Two green areas
   LCD.fill_rect(0,48,112,16,LCD.GREEN)
   LCD.fill_rect(0,80,112,16,LCD.GREEN)
# Two yellow areas
   LCD.fill_rect(96,48,16,16,LCD.YELLOW)
   LCD.fill_rect(96,80,16,16,LCD.YELLOW)
# Two red areas
   LCD.fill_rect(112,48,16,16,LCD.RED)
   LCD.fill_rect(112,80,16,16,LCD.RED)
# Left channel pointer
   LCD.line(lpos,46,lpos,66,LCD.WHITE)
# Right channel pointer
   LCD.line(rpos,78,rpos,98,LCD.WHITE)
# Display the meter face
   LCD.show()
   utime.sleep(delay)
   LCD.fill(0)
```

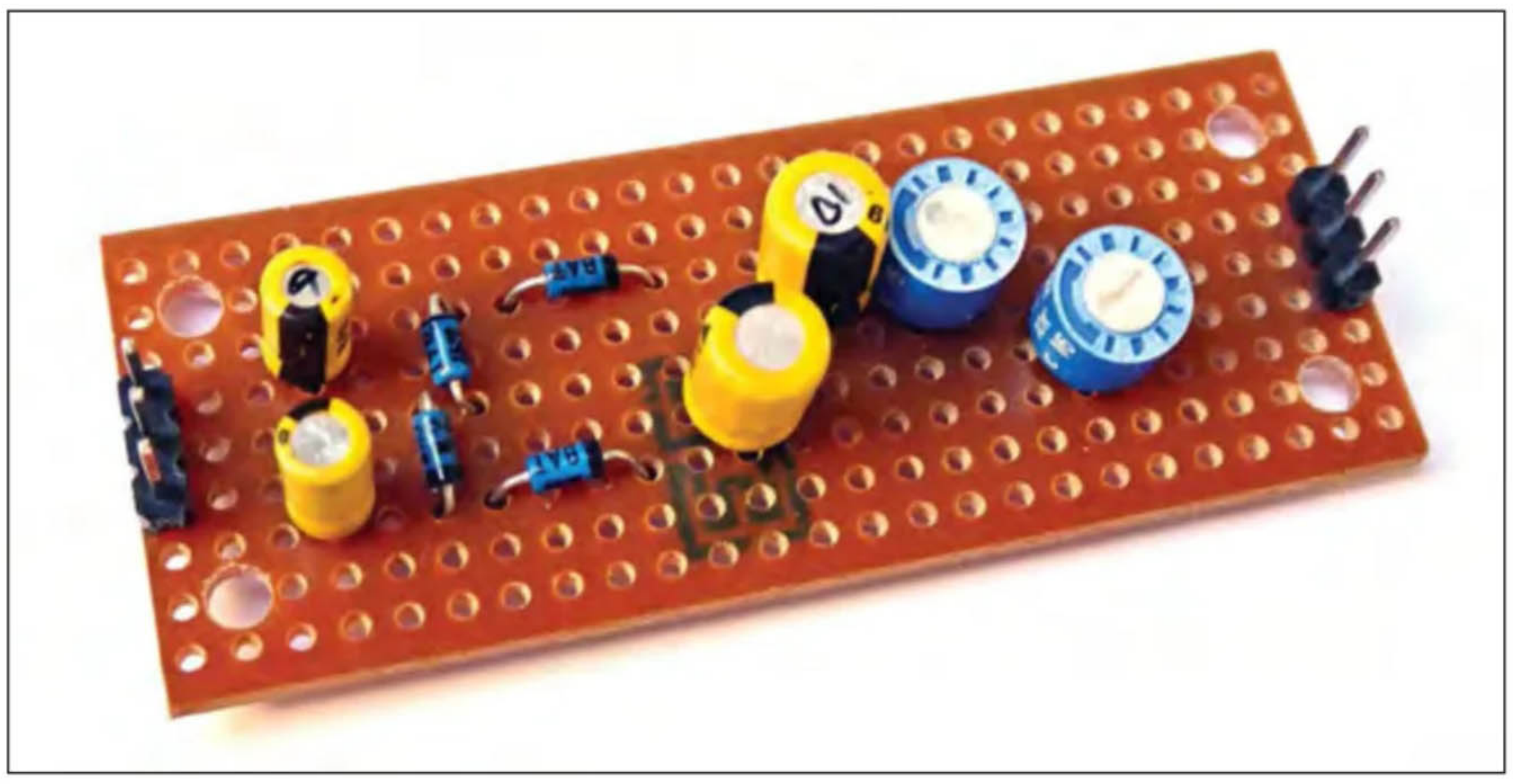


Fig.13.11. Signal-level detector stripboard.

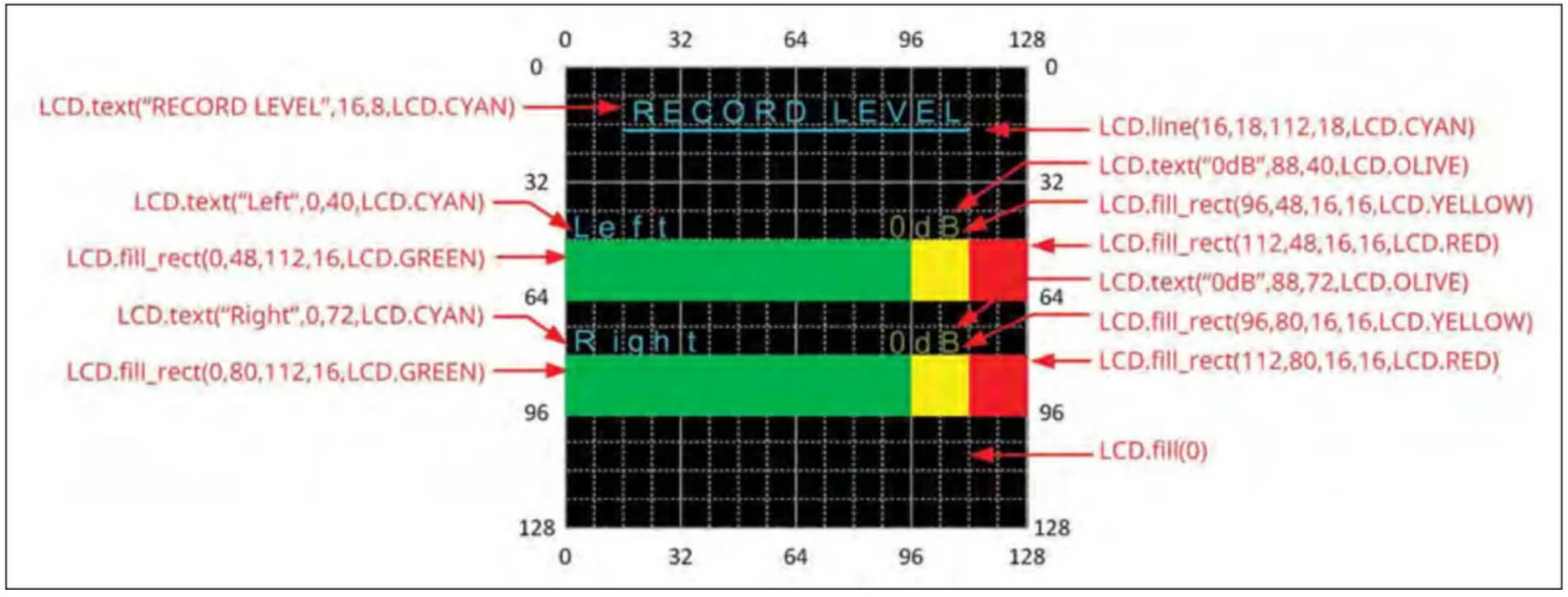

0
32
64
96
128
0
LCD.text("RECORD LEVEL",16,8,LCD.CYAN)
RECORD LEVEL
LCD.line(16,18,112,18,LCD.CYAN)
LCD.text("0dB",88,40,LCD.OLIVE)
32
LCD.text("Left",0,40,LCD.CYAN)
LCD.fill_rect(96,48,16,16,LCD.YELLOW)
Left
0dB
LCD.fill_rect(0,48,112,16,LCD.GREEN)
LCD.fill_rect(112,48,16,16,LCD.RED)
LCD.text("0dB",88,72,LCD.OLIVE)
64
LCD.text("Right",0,72,LCD.CYAN)
LCD.fill_rect(96,80,16,16,LCD.YELLOW)
Right
0dB
LCD.fill_rect(0,80,112,16,LCD.GREEN)
LCD.fill_rect(112,80,16,16,LCD.RED)
96
LCD.fill(0)
128
0
32
64
96
128

Fig.13.12. Screen layout (using the template shown earlier in Fig.13.6).

would be beneficial to use screened cable.

Simply connect the USB cable and then select Tools and Options from the Thonny's menu bar (see Fig.13.8). Next, select the RPi Pico interpreter and the appropriate USB port (see Fig.13.9). When this has been done you can transfer your code by clicking on Thonny's 'Run' icon.

Coding

With a project like this it's worth starting by sketching your required layout and identifying all the features that need to be displayed (see Fig.13.12). To assist with this task, you may find one of the templates shown earlier useful.

Coding for the audio signal level meter is straightforward. We used the RPi Pico's ADC0 and ADC1 inputs for the left and right channels respectively. These are respectively mapped to the RPi's GP26 and GP27 pins. The returned data values, (`left_data` and `right_data`) are used to determine the horizontal axis deflection of the two pointers (corresponding to `lpos` and `rpos` respectively).

The display buffer is then created, starting with the legend text before adding the coloured areas for each of the meter scales. The two pointers are added to the display using the `lpos` and `rpos` positional information before finally sending the buffer to the LCD for one second, after which the entire process is repeated with the pointers updated to a new position where appropriate. The code fragment in Listing 4 shows how this is done.

Parts

To build the recording level signal indicator you will need:

Perforated copper stripboard (9 strips, each with 25 holes)
2 3-way headers
2 10kΩ miniature pre-set resistors (RV1 and RV2)
2 1µF 35V radial lead electrolytic capacitors (C1 and C2)
2 47µF 25V radial lead electrolytic capacitors (C3 and C4)
4 BAT42 Schottky signal rectifier diodes (D1 to D4)

Going further

This section details a variety of sources that will help you locate the component parts and further information that will allow you to acquire and get the best out of your Raspberry Pi Pico display. It also provides links to relevant underpinning knowledge as well as some manufacturers' data.

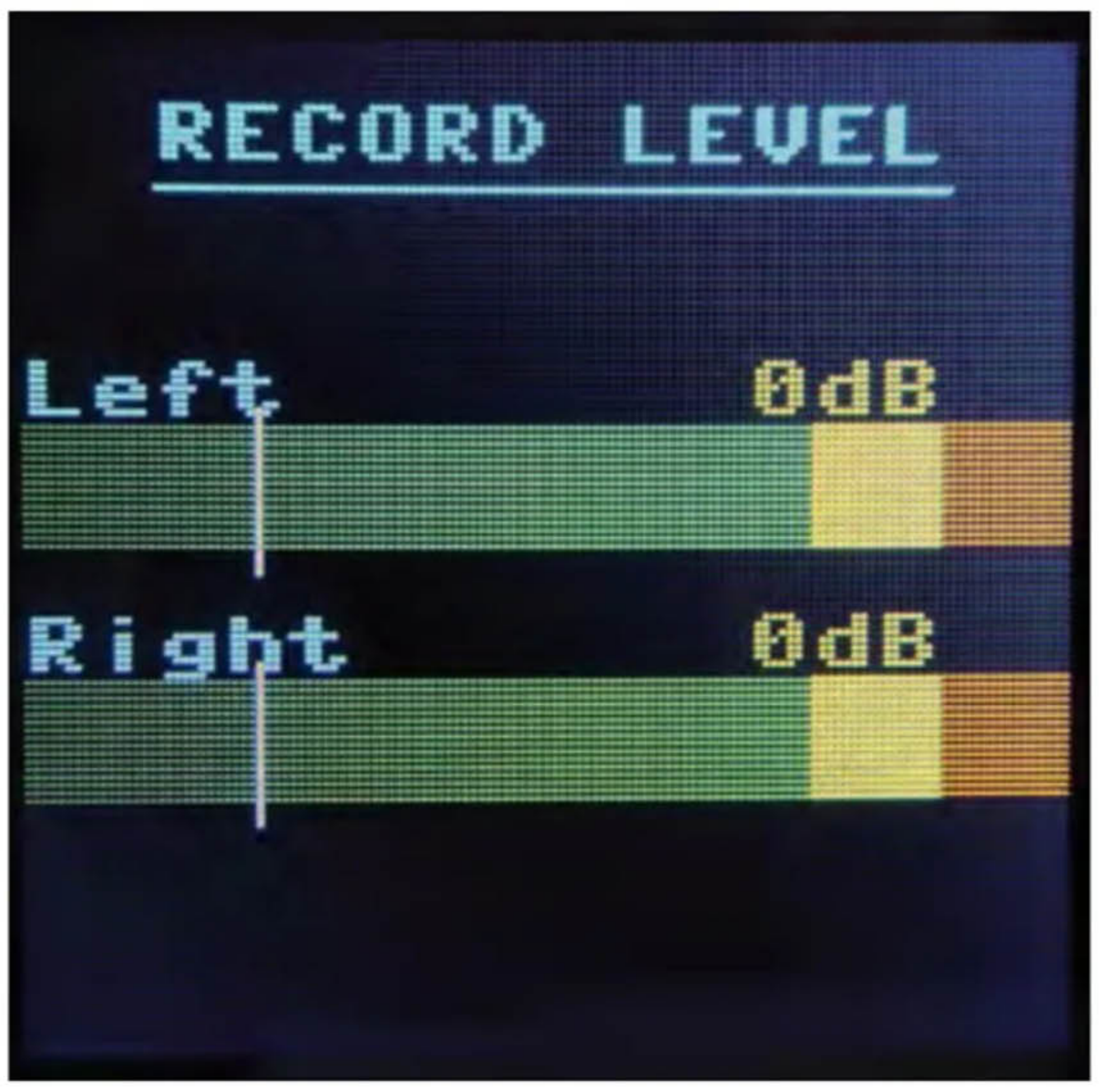


Fig.13.13. Close-up view of the display.

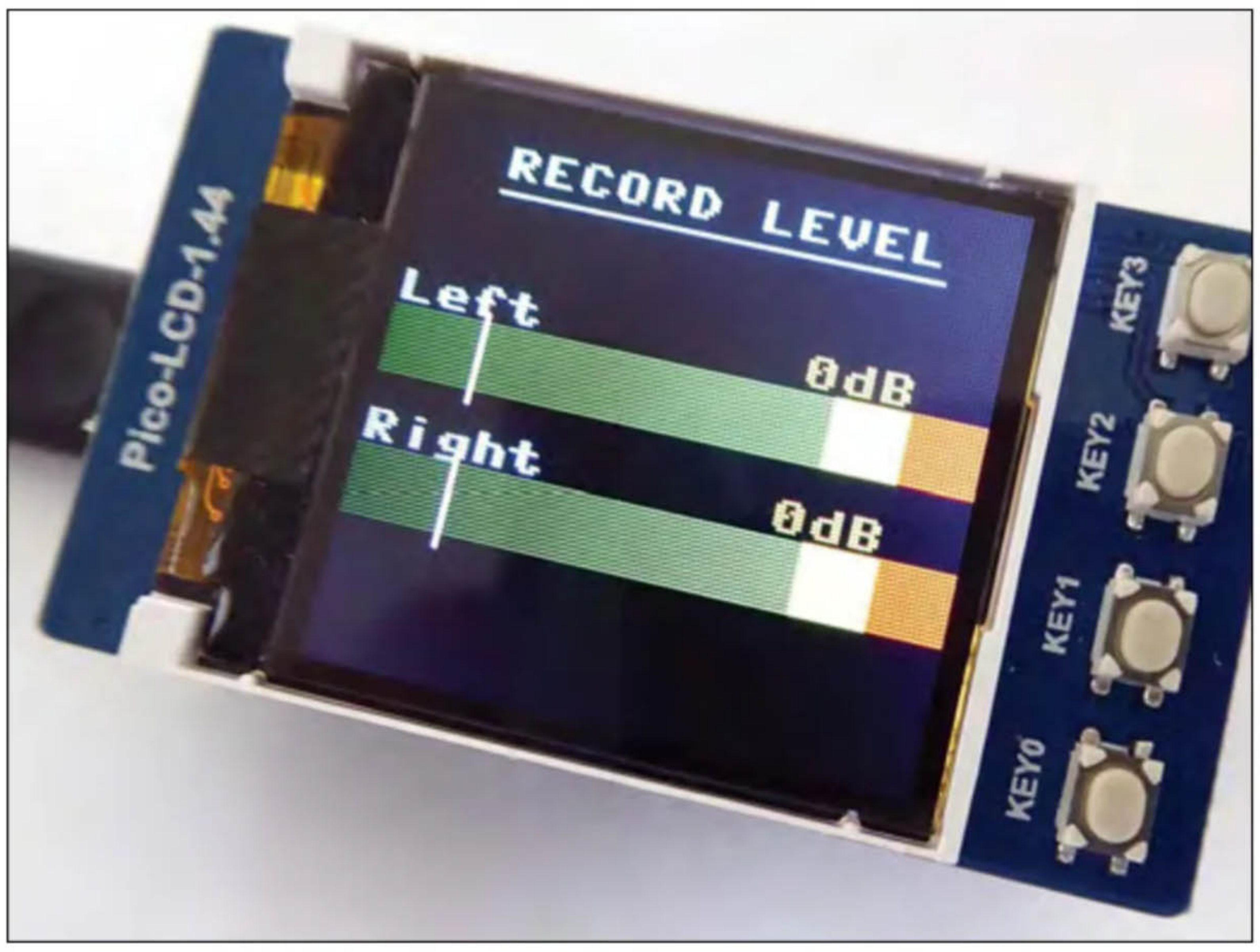
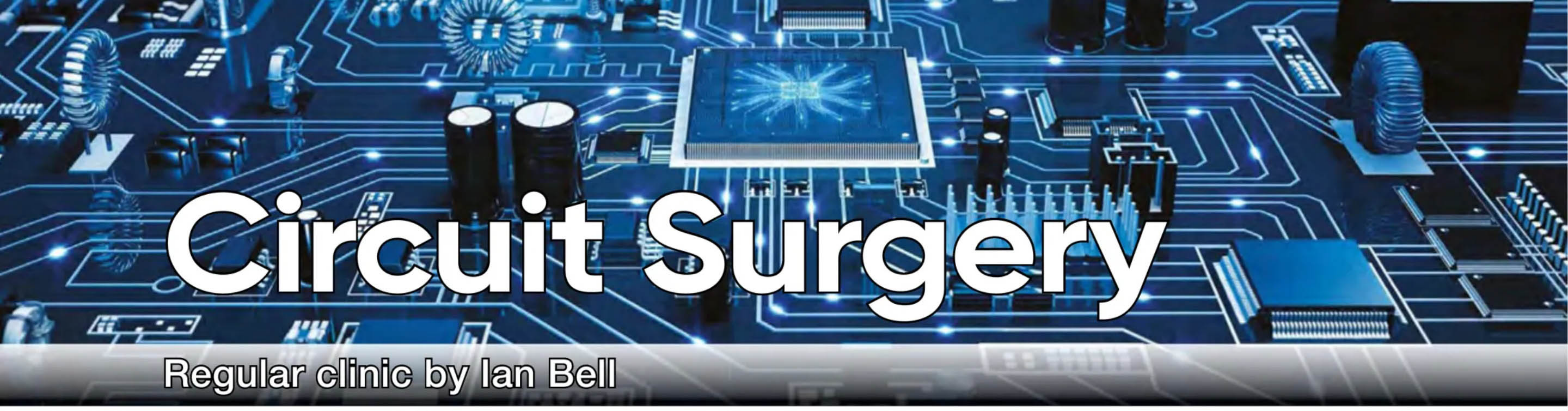


Fig.13.14. The finished RPi Pico recoding level indicator (the four button keys can be used for a variety of other functions such as dimming the display or changing the display appearance).

Table 13.3 Going further with the low-cost colour LCD displays and the RPi Pico

Topic	Source	Notes
RPi Pico boards	Numerous suppliers: eg, The Pi Hut (**www.thepihut.com**) offer RPi Pico boards, both with and without headers	Boards with headers cost more than those without. Soldering skills will be required to solder your own headers!
RPi Pico, MicroPython and Thonny	*KickStart Part 8* (*PE*, May 2022) provides a general introduction to the RPi Pico and it includes details of installing the MicroPython firmware as well as coding using MicroPthyon and Thonny	For back issues of *PE* please visit: **https://bit.ly/pe-backissues**
Back-pack display modules	*Part 38* of Phil Boyce's popular *Make it with Micromite* series (*PE* August 2022) provides useful information on selecting and using different types of display backpack displays (including the larger 2.8-inch and 3.5-inch Waveshare modules offering resolutions of 320×240 and 480×320 pixels respectively)	For back issues of *PE* please visit: **https://bit.ly/pe-backissues**
1.4-inch Pico LCD	Documentation and demonstration programs (including display driver) from: **https://bit.ly/pe-oct23-144**	
1.8-inch Pico LCD	Documentation and demonstration programs (including display driver) from: **https://bit.ly/pe-oct23-18**	
Driver and sample code	Driver and sample code for the 1.44-inch and 1.8-inch Waveshare LCD modules is available for download from the *PE* website: **https://bit.ly/pe-downloads**	RGB colour conversion utilities and PDF layout templates are available from the *PE* website: **https://bit.ly/pe-downloads**
MicroPython and Thonny	The latest documentation for MicroPython at: **https://docs.micropython.org/en/latest/** The latest version of Thonny for Windows, Mac or Linux from: **www.thonny.org**	
RPi Pico books	The official RPi Pico guide is *Get Started with Micropython on Raspberry Pi Pico* by Gareth Halfacre and Ben Everard (ISNB 978-1-912-04786-4). It provides an introduction to the RPi Pico; plus, using Thonny, it describes a variety of simple projects suitable for beginners. *Programming the Pico – Learn Coding and Electronics with the Raspberry Pi Pico* (ISBN 979-8-464-88217-1) – another excellent introductory book from Simon Monk.	These two books are intended for complete beginners and they both assume little previous knowledge of electronics and coding
Waveshare colour LCD	Details of the full range of Waveshare displays is available from: **https://bit.ly/pe-oct23-wave**	A wide variety of Waveshare colour LCD modules are available from on-line suppliers
RPi Pico projects	**https://bit.ly/pe-may22-pico1**	This useful beginners' guide shows you how to connect a RPi Pico to a computer, install the Thonny Python IDE and write a MicroPython program to blink the Pico's onboard LED



Circuit Surgery

Regular clinic by Ian Bell

Gyrators Part 2 – Equaliser Circuits

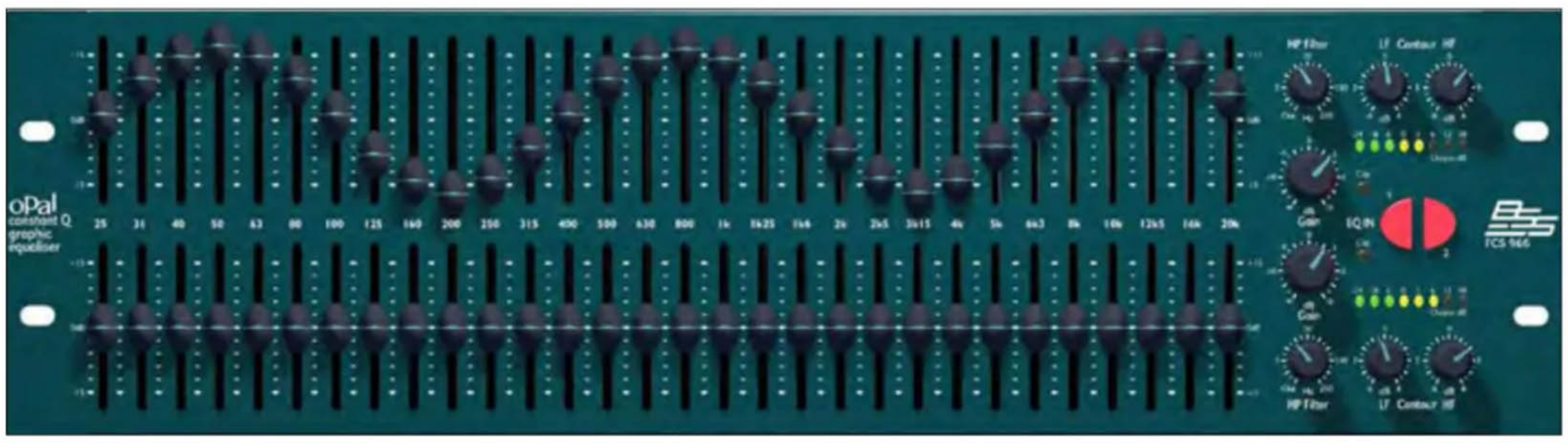


Fig.1. Graphic equaliser.

Last month, we started to look at gyrator circuits following a mention of their use in a response to a post on the EEWeb forum. Gyrators are part of a range of fascinating circuits, often with niche applications, that can generally be described as 'impedance converters'. In terms of its formal definition, a gyrator is like a variant of the transformer which converts input voltage to output current, and vice versa, with a scaling factor called gyration resistance. In more practical terms, a key property of gyrators is that they can be used to create circuits that behave 'like inductors' without actually using any inductors. They effectively 'impedance convert' a capacitor to an inductor.

Where large inductors are required, the total weight, size and cost of a gyrator-based implementation can be much lower. Furthermore, real inductors tend to be less ideal and suffer from more problems than real capacitors, so converting a good quality capacitor to an inductor may give good performance despite the additional circuitry. A common use of gyrators is to implement resistor-inductor-capacitor (*RLC*) resonant circuits for use in bandpass or bandstop (notch) filters. The fact that the effective inductance of a gyrator is controlled by a resistor means that it is relatively straightforward to make such filters tuneable – a potentiometer can be used, so a variable capacitor or inductor is not required.

Perhaps the best-known use of gyrator-based filters is in analogue audio equalisers, which require multiple bandstop/bandpass filters, so this month we'll look at the circuitry involved.

Equalisers

Equalisers provide a means of adjusting the volume of an audio signal within a set of different frequency bands. This allows much more specific control of the sound than simple bass and treble controls. Equalisers are used in a range of situations and applications, including recording studios, sound systems in live venues and guitar pedals. Equalisers require a set of filters which can provide either cut or boost to the signal within a specified range – that is, a set of filters which can be adjusted to provide bandpass or bandstop behaviour at the required frequencies.

Graphic equalisers (see Fig.1) typically have a number of sliders to adjust signal cut and boost in a set of fixed frequency bands. Some equalisers (for example, in recording studios) have 31 bands, but others, such as guitar pedals, have fewer. Typically, each band provides boost or cut of up to ±12 to ±15dB. The centre frequency of each band varies logarithmically – each band is at a fixed multiple of the previous band, typically ×2 (octave), $\times\sqrt{2} = \times 1.414$ (half octave), or $\times\sqrt[3]{2} = \times 1.260$ (third octave). The specific frequencies are standard in the industry.

Parametric equalisers provide more control over each band than graphic equalisers, with adjustable frequency and possibly bandwidth. They may also be switchable between peaked (bandpass/bandstop) and high-pass/low-pass response (referred to as a 'shelving' response in audio jargon). They are more complex, and to be used effectively they require a deeper understanding of the impact of settings on the sound and other equipment compared to simpler graphic equalisers.

The fact that gyrators' behaviour can be modified via variable resistors makes them suitable for parametric equalisers as well as inductor-less graphic equalisers. Of course, modern sound processing is often done digitally and equalisation is no exception; however, analogue systems are still used and the circuits are interesting to investigate.

Gyrator circuit recap

One of the simplest and most popular gyrator circuits is shown in Fig.2. We discussed this in detail last month and showed that the equivalent inductor is not perfect, even if the circuit is built with ideal components. There is some series and parallel resistance (see Fig.3). The values in Fig.2 and Fig.3 are related as follows:

$$L = (R_1 - R_2)R_2C$$

$$R_S = R_2$$

$$R_P = R_1 - R_2$$

A real op amp will introduce further imperfections, particularly at high frequencies where it bandwidth limits the circuit (discussed last month). The op amp slew rate will also limit the response to fast changing inputs.

Cut and boost

To make an equaliser we need filters which can vary between bandstop or

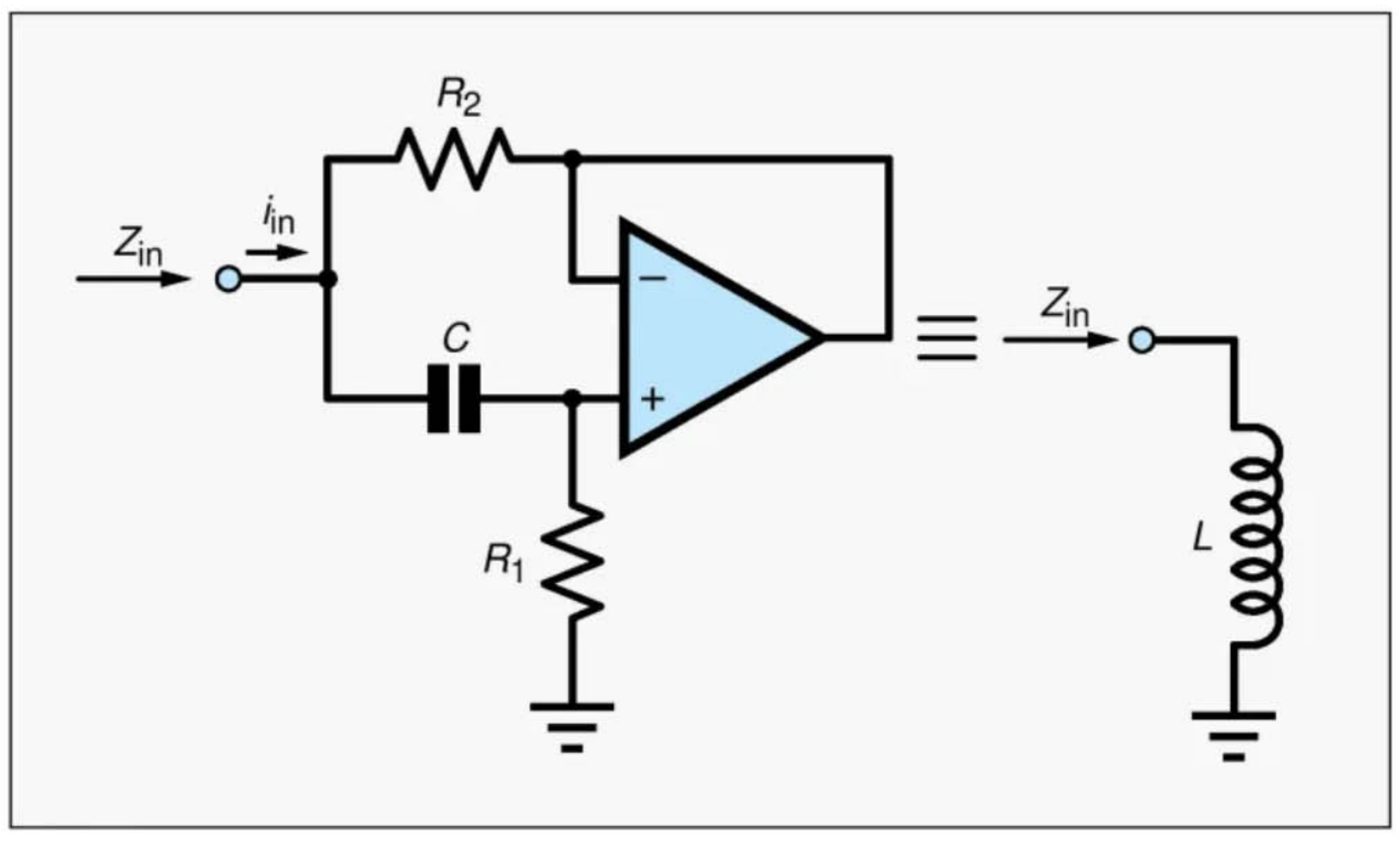


Fig.2. Gyrator circuit to produce behaviour equivalent to an inductor.

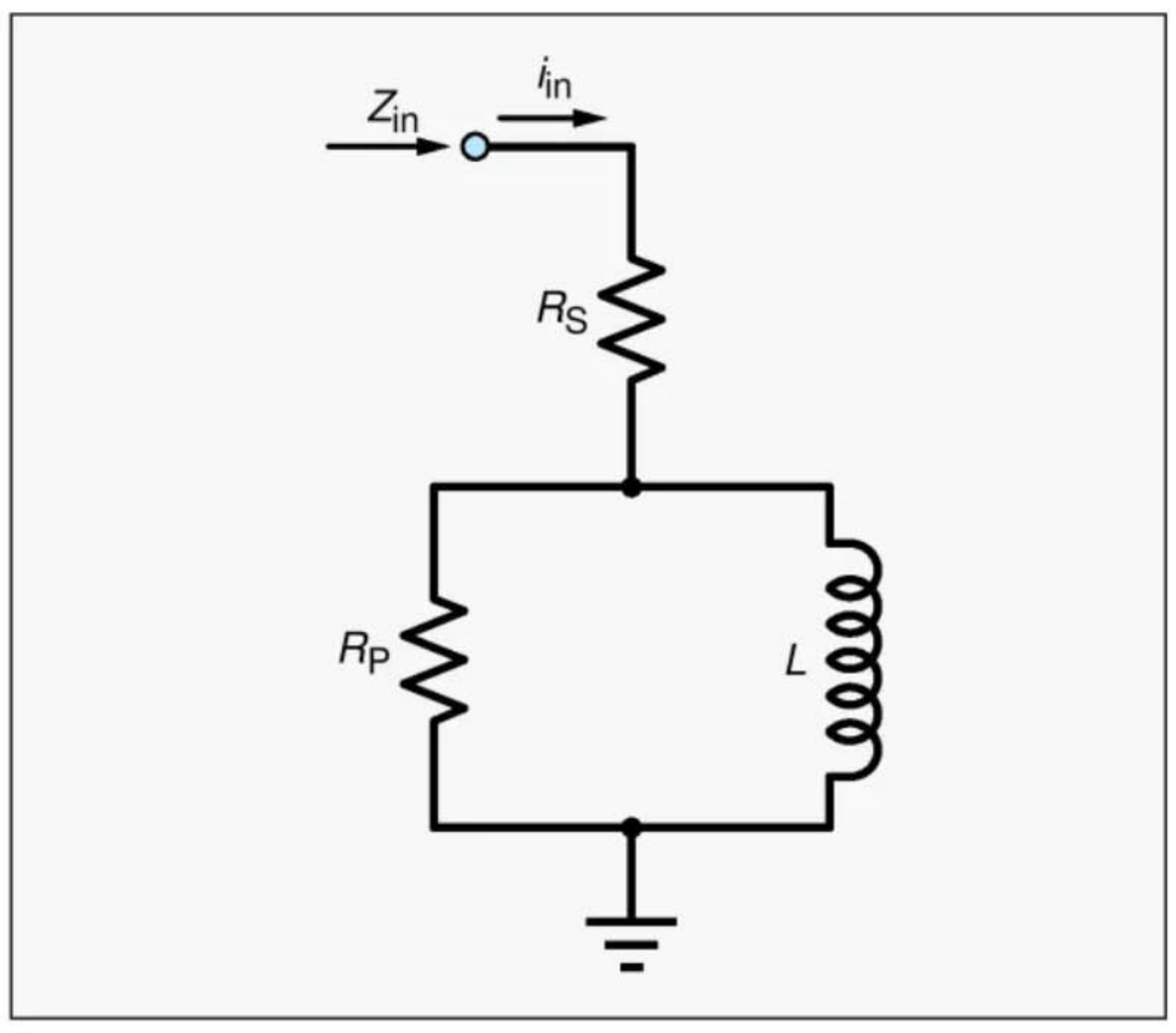


Fig.3. Equivalent circuit for the gyrator shown in Fig.2.

bandpass at a given centre frequency; one that can be adjusted continuously between some maximum attenuation and maximum gain. The amount of attenuation or gain needs to be adjustable by a single control (potentiometer) which does not affect the centre frequency of the filter as it is changed. If the 'amount' is set to maximum boost (gain) the circuit will act as a relatively strong bandpass filter at the centre frequency. If the amount is set to a maximum cut (attenuation) the circuit will act as a relatively strong bandstop filter at the centre frequency. In the middle of this range will be a neutral point where there is no filtering – the circuit has unity gain at all frequencies. Increasing the gain from the neutral point will result in an increasing strong peak in the bandpass response, and similarly for bandstop in the attenuation direction. For a graphic equaliser, each band will have a cut/boost (amount) control at a fixed frequency. For a parametric equaliser, the centre frequency and possibly other parameters can also be adjusted.

Fig.4 is a cut and boost circuit which provides the gain control function we require. A basic form of the circuit, which does not include any filtering is shown. We will describe its operation in terms of gain and attenuation adjustment before looking at how the filtering is included.

Like the gyrator, this is not the easiest of circuits to intuitively understand, but we can look at the full cut and full boost operation reasonably straightforwardly to determine the gain/attenuation range. The potentiometer R_P is the cut/boost control, with the maximum effects occurring at the ends of the potentiometer range as shown. The input resistor and feedback resistors must have the same value (R_{IF}). The grounded resistor (R_G) is replaced by a frequency-dependent circuit to implement a filter.

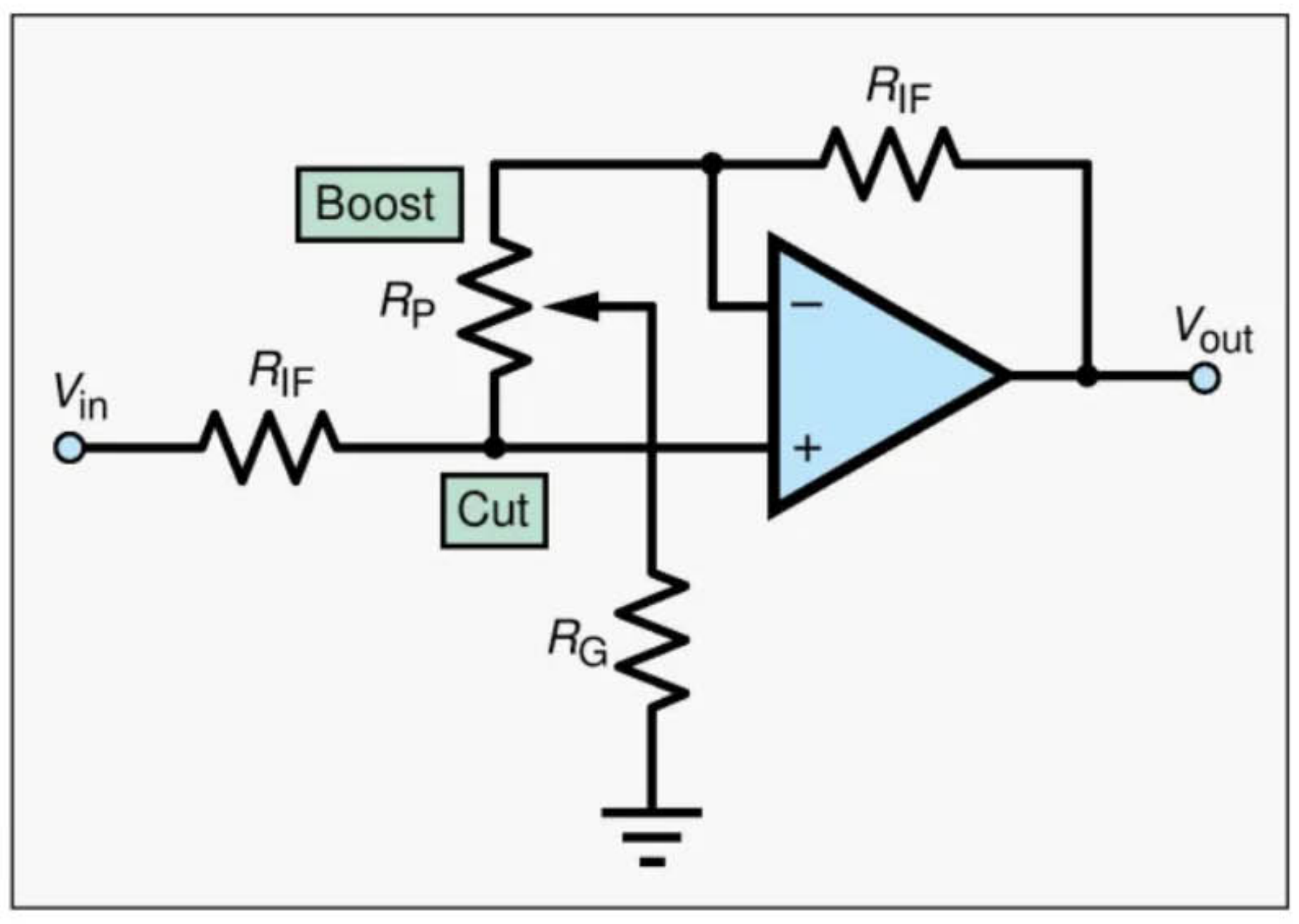


Fig.4. Cut/boost circuit.

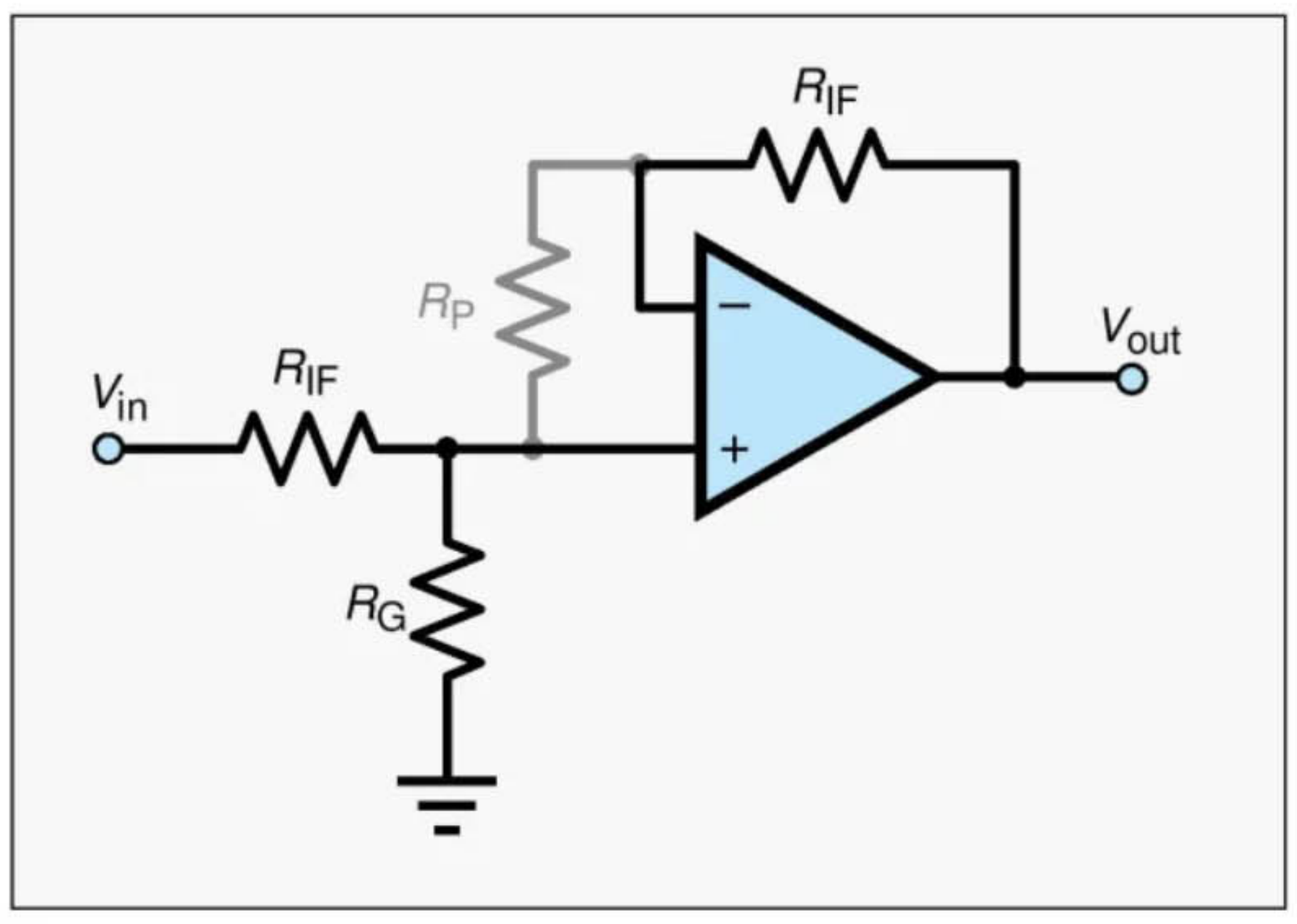


Fig.5. Cut/boost circuit – equivalent circuit in full cut mode.

As is commonly done in the analysis of linear op amp circuits with negative feedback, we assume that the op amp controls its output to achieve zero volts across its inputs. This means that the voltage across R_P is always zero, however, this does not mean the current in R_P is always zero because current flowing through the wiper can produce equal and opposite voltages across the two parts of the potentiometer track. We also make use of the common assumption in op amp circuit analysis that zero current flows into the op amp's input.

Equivalent circuits

Fig.5 shows the situation with the potentiometer wiper fully at the cut end. The circuit is effectively a potential divider, formed by the input resistor (R_{IF}) and R_G, connected to a unity-gain amplifier (the feedback resistor provides 100% feedback). The potentiometer resistance (shown faded out) has very little effect on the circuit because, as just noted, it has zero voltage across it and current in R_G does not flow through it. The circuit therefore acts as an attenuator with the gain set by the potential divider effect. Using the potential divider equation, we get:

$$A_{Cut} = \frac{R_G}{R_{IF} + R_G}$$

Fig.6 shows the situation with the potentiometer wiper fully at the boost end. The circuit is effectively a standard non-inverting op amp amplifier, with the gain set in the usual way by the feedback (R_{IF}) and grounded (R_G) resistors. Again, the potentiometer resistance (shown faded out) has very little effect on the circuit for the same reasons as the full cut case. The gain is given by the non-inverting amplifier formula:

$$A_{Boost} = 1 + \frac{R_{IF}}{R_G} = \frac{R_{IF} + R_G}{R_G}$$

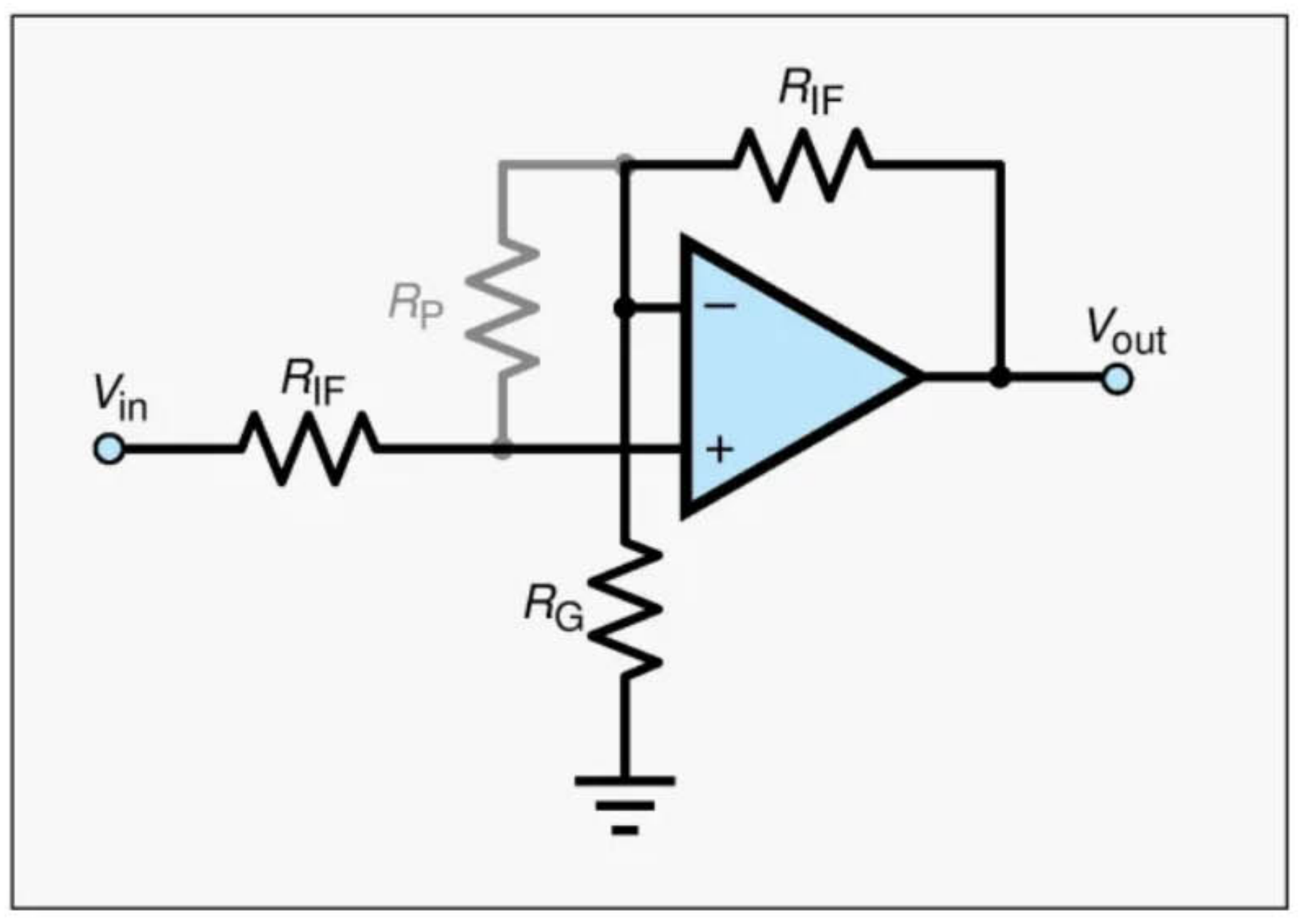


Fig.6. Cut/boost circuit – equivalent circuit in full boost mode.

We can see that the cut and boost gains are reciprocals ($A_{Cut} = 1/A_{Boost}$). This means in decibels A_{Cut} dB = $-A_{Boost}$ dB, so the circuit has symmetrical maximum cut and boost.

Fig.7 shows the general case where the wiper is not at the extreme ends of the potentiometer. The potentiometer is represented as two resistors (R_{P1}, R_{P2}) – the track resistances from the wiper to the two ends. Consider what happens when the wiper is exactly in the middle of the track, so $R_{P1} = R_{P2}$. As previously noted, the voltage across the potentiometer is zero, which means that $V_{P1} = V_{P2}$. With the wiper at the halfway position the two parts of the potentiometer track resistance (R_{P1} and R_{P2}) are equal, therefore, for V_{P1} and V_{P2} to have equal magnitudes the currents I_F (feedback current) and I_{In} (input current) must be equal too. The current in the feedback resistor is equal to the current in R_{P1} (as shown) because we assume that no current flows into the op amp input. Similarly, the current in R_{P2} is equal to the input current.

The feedback and input resistors are at the same voltage at their op-amp-input ends due to the zero voltage difference between the op amp's inputs. Given that the currents through them and their resistances are also equal, the voltages at their other ends must be equal too. Therefore, the input and output voltages must be equal. We conclude that when the potentiometer wiper is at the centre position the circuit has unity gain.

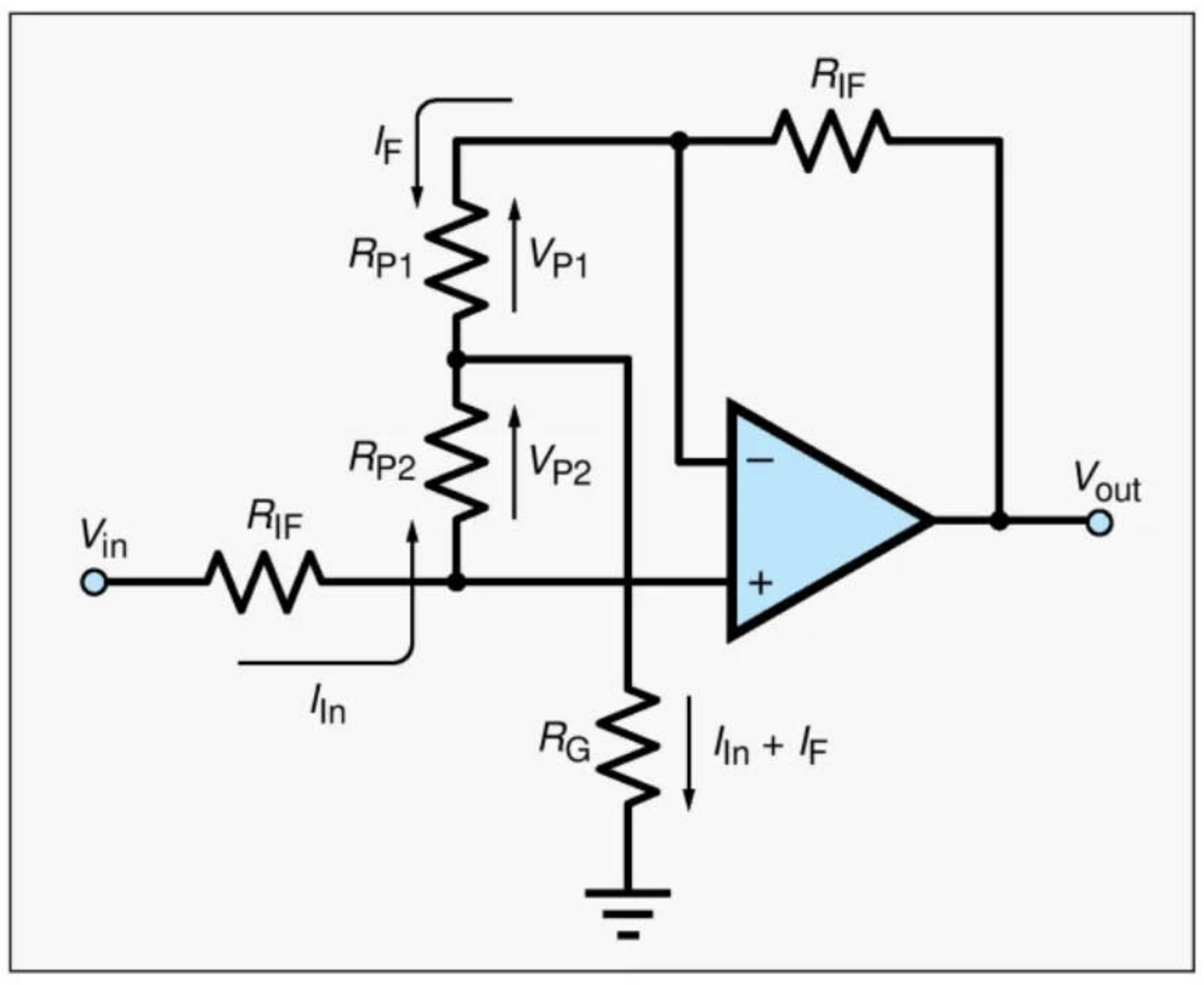


Fig.7. Cut/boost circuit – wiper part way along track.

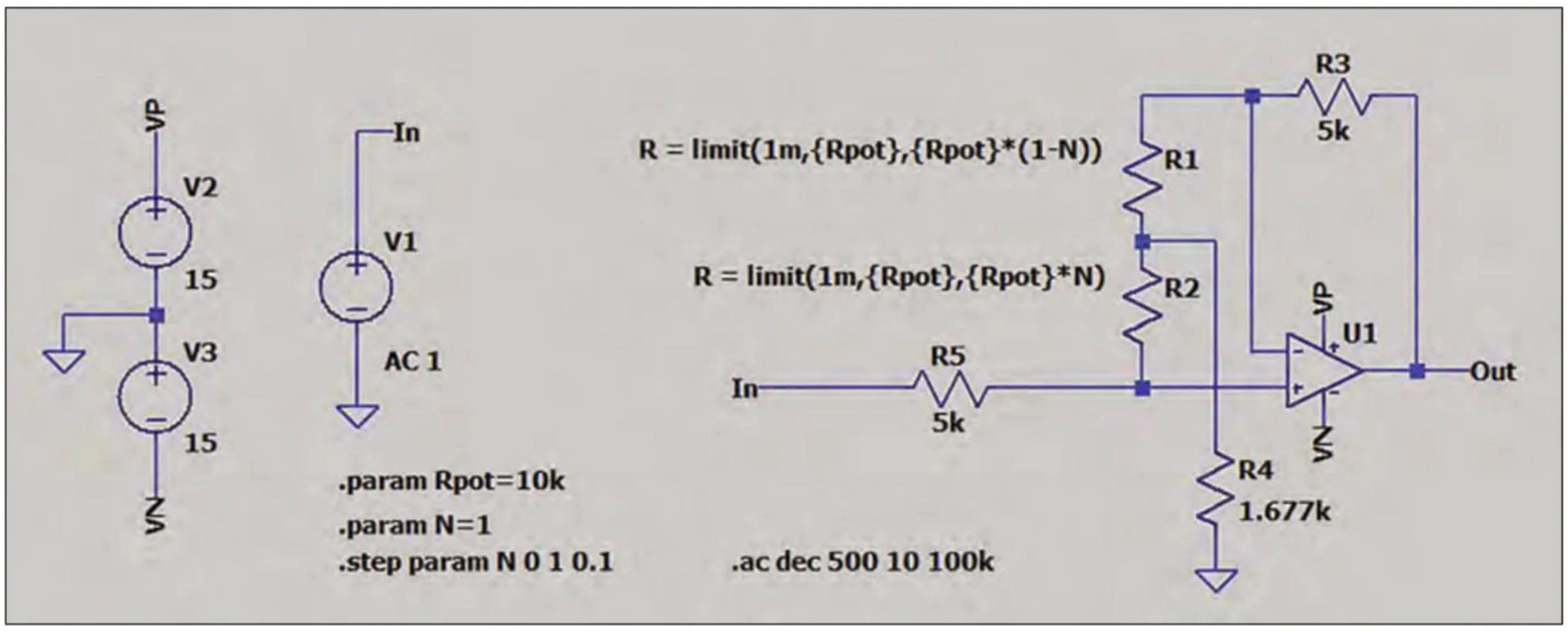


Fig.8. Cut/boost circuit LTspice schematic.

Component values and simulation

Selection of component values is fairly straightforward. The value of the potentiometer is not very critical – it does not affect the full cut and boost gains or the midpoint unity gain but will have some influence on intermediate values. Values in the range 5kΩ to 20kΩ are usually suitable, and 10kΩ is typical. Larger values are acceptable, but larger resistances will cause more noise in the circuit. The values of R_G and R_{IF} are found based on the required maximum cut/boost and will typically be in the range of a few kiloohms. For example, if we want a full boost gain of 12dB (= $\times 10^{12/20}$ = ×3.981) and we choose R_{IF} = 5kΩ, then from the non-inverting amplifier gain formula R_G = 5000/(3.981 – 1) = 1.677kΩ. The full cut gain will be –12dB.

To simulate the cut/boost circuit in LTspice we need to model the potentiometer as we vary the wiper position. If we define the wiper position as a value N, where $N = 0$ with the wiper at one end and $N = 1$ with the wiper at the other, then $R_{P2} = NR_P$ and $R_{P1} = (1 - N)R_P$. In LTspice we can use a node voltage or parameter value to control N and vary this in the simulation. We can implement the two resistance formulae using behavioural resistors but need to prevent the resistors from becoming zero or negative in value. This can be done with an LTspice limit function. We discussed modelling a potentiometer in this way in more depth in *Part 5* of our series on *Electronically Controlled Resistance* (*Circuit Surgery*, January 2023).

Fig.8 shows an LTspice schematic for simulating the cut/boost circuit using the values just discussed and implementing the potentiometer as described in the previous paragraph. The wiper position is set using a parameter value (N) that is stepped over 11 values from 0 to 1 (step of 0.1). The results are shown in Fig.9 and confirm the full cut and boost are –12 and +12dB respectively, and that the gain for $N = 0.5$ (wiper halfway) is unity (0dB). The frequency response curves are flat because the circuit has no frequency-dependent components and the range is below the bandwidth of the semi-idealised op amp model (LTspice `UniversalOpamp2`, as used last month).

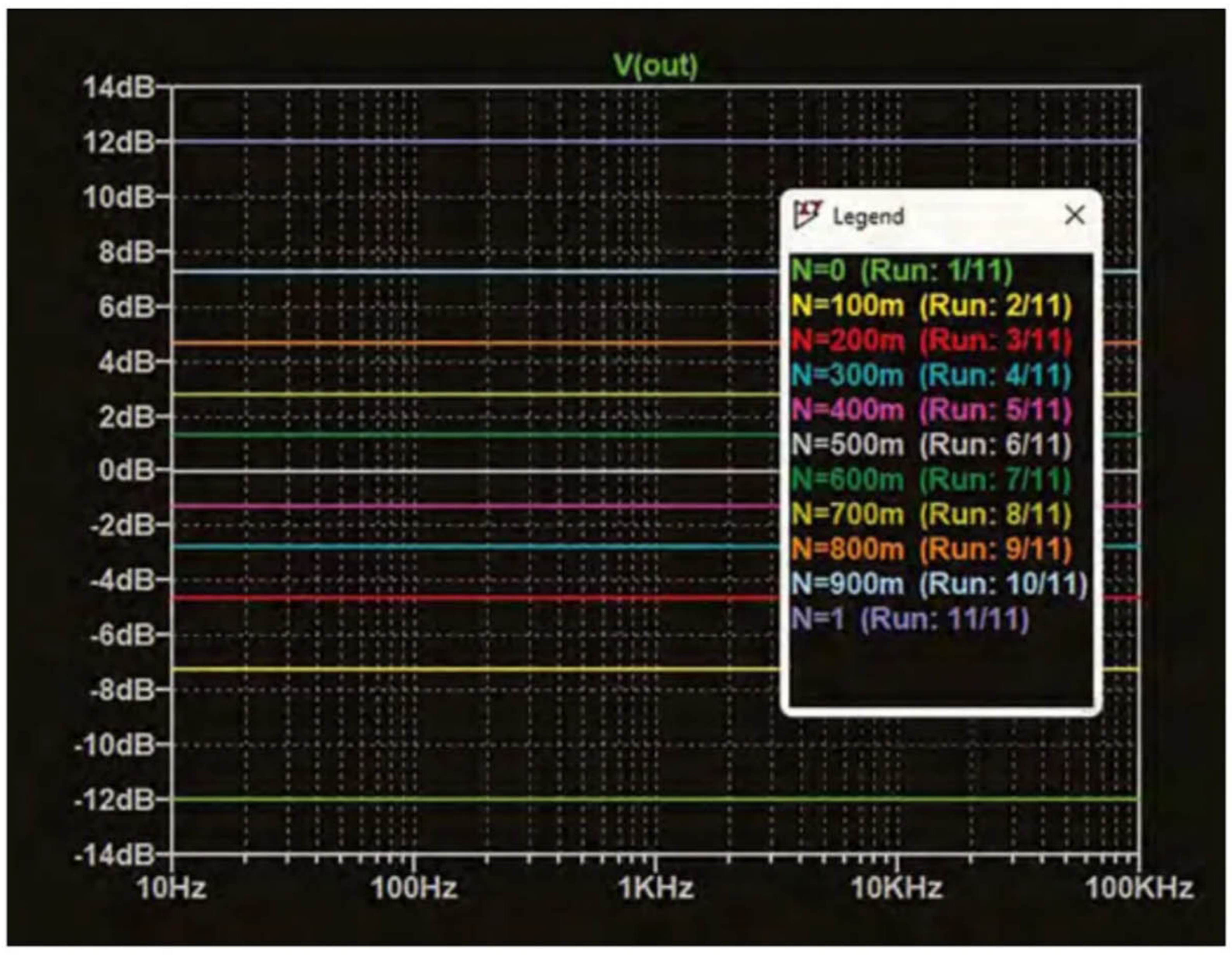


Fig.9. Results from simulation of circuit in Fig.8.

Effect of R_G

The amount of boost or cut (except at the unity gain central point) depends on the value of the grounded resistor. Increasing R_G reduces the gain in the boost half of the wiper range (note that full boost (A_{Boost}) is inversely proportional to R_G). Increasing R_G also reduces the amount of attenuation in the cut range (similarly, full cut (A_{Cut}) is proportional to R_G – increasing A_{Cut} (gain) means a reduction in attenuation). So, depending on which half of the pot the wiper is on, changing R_G has the same effect on either the amount of cut or the amount of boost.

As R_G tends towards infinity (open circuit) the gain becomes unity for all wiper positions – the equations for full boost and cut (A_{Boost} and A_{Cut}) given above both simplify to $\approx R_G/R_G = 1$ if R_G is much larger than R_{IF} so that $(R_G + R_{IF}) \approx R_G$. Fig.10 shows the equivalent circuit of the cut/boost circuit with infinite R_G. We see that it is an inverting amplifier (100% feedback). The input resistor has no effect, assuming zero current flow into the op amp (zero voltage drop across it). R_P has little effect as the wiper is effectively disconnected and there is zero volts across it, as previously discussed.

We can demonstrate the effect of the value of R_G by altering the circuit in Fig.5 to make the value of R_G a parameter and step this through a range of resistor values (with a fixed wiper position). The results are shown in Fig.11 and Fig.12 and are for a wiper position halfway into the boost and cut ranges (N = 0.75 and N = 0.25 respectively). In each case, a given resistance

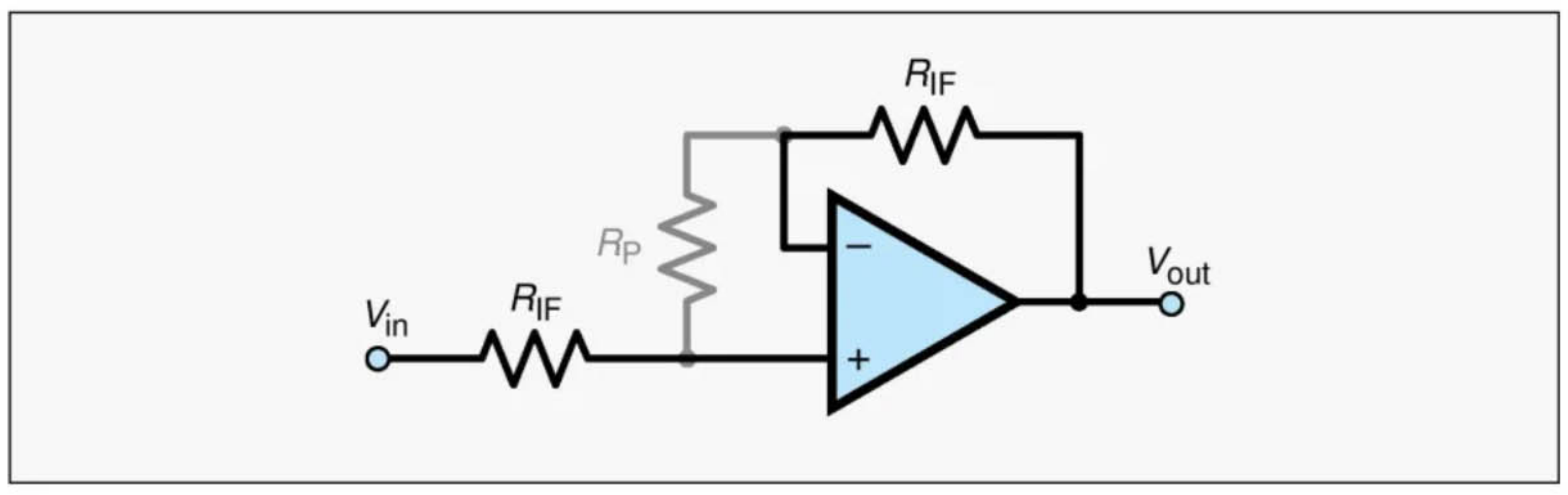


Fig.10. Cut/boost circuit – equivalent circuit with infinite R_G.

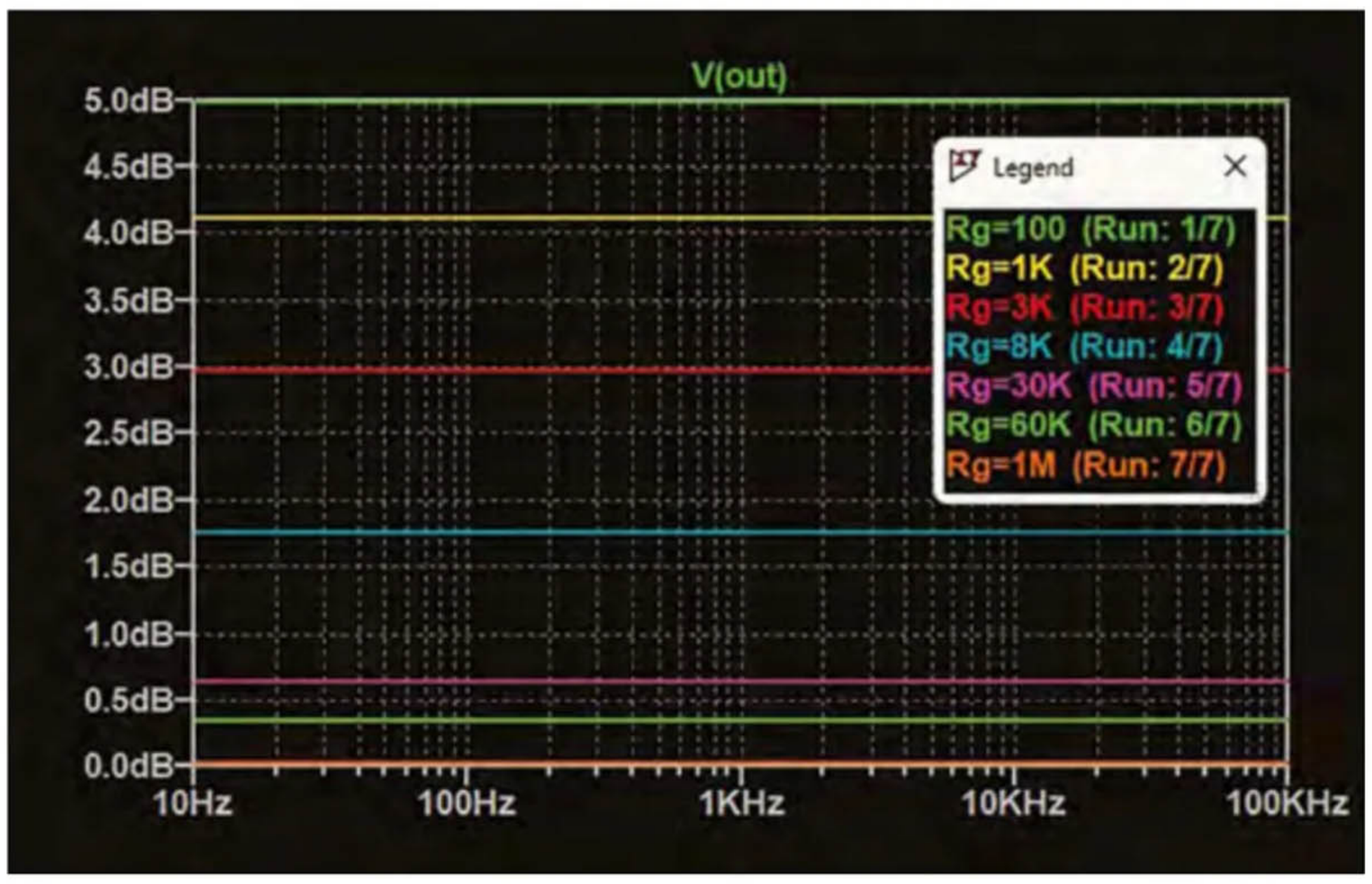


Fig.11. Simulation results for various R_G values in the cut/boost circuit with wiper position N = 0.75 (boost).

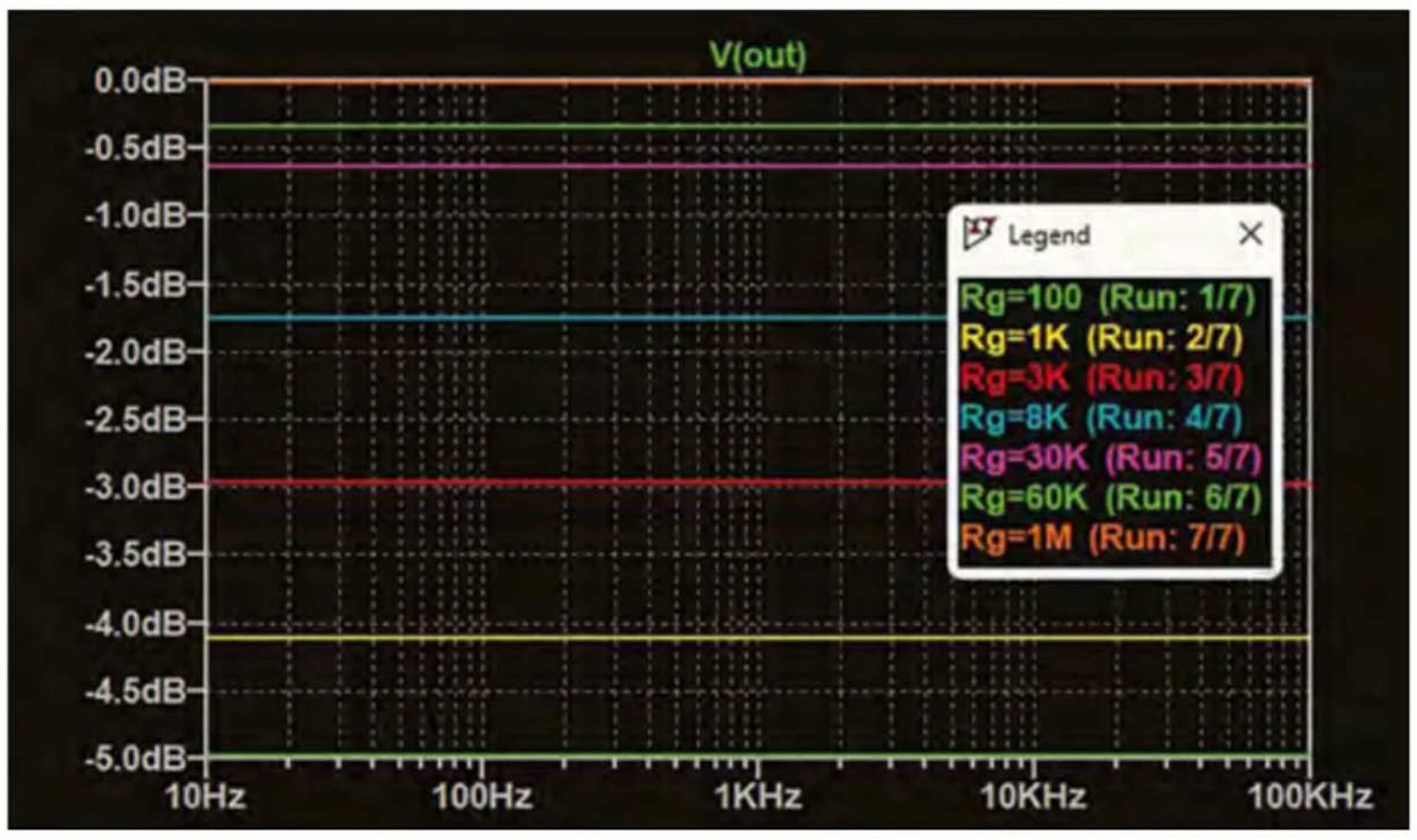


Fig.12. Simulation results for various R_G values in the cut/boost circuit with wiper position N = 0.25 (cut)

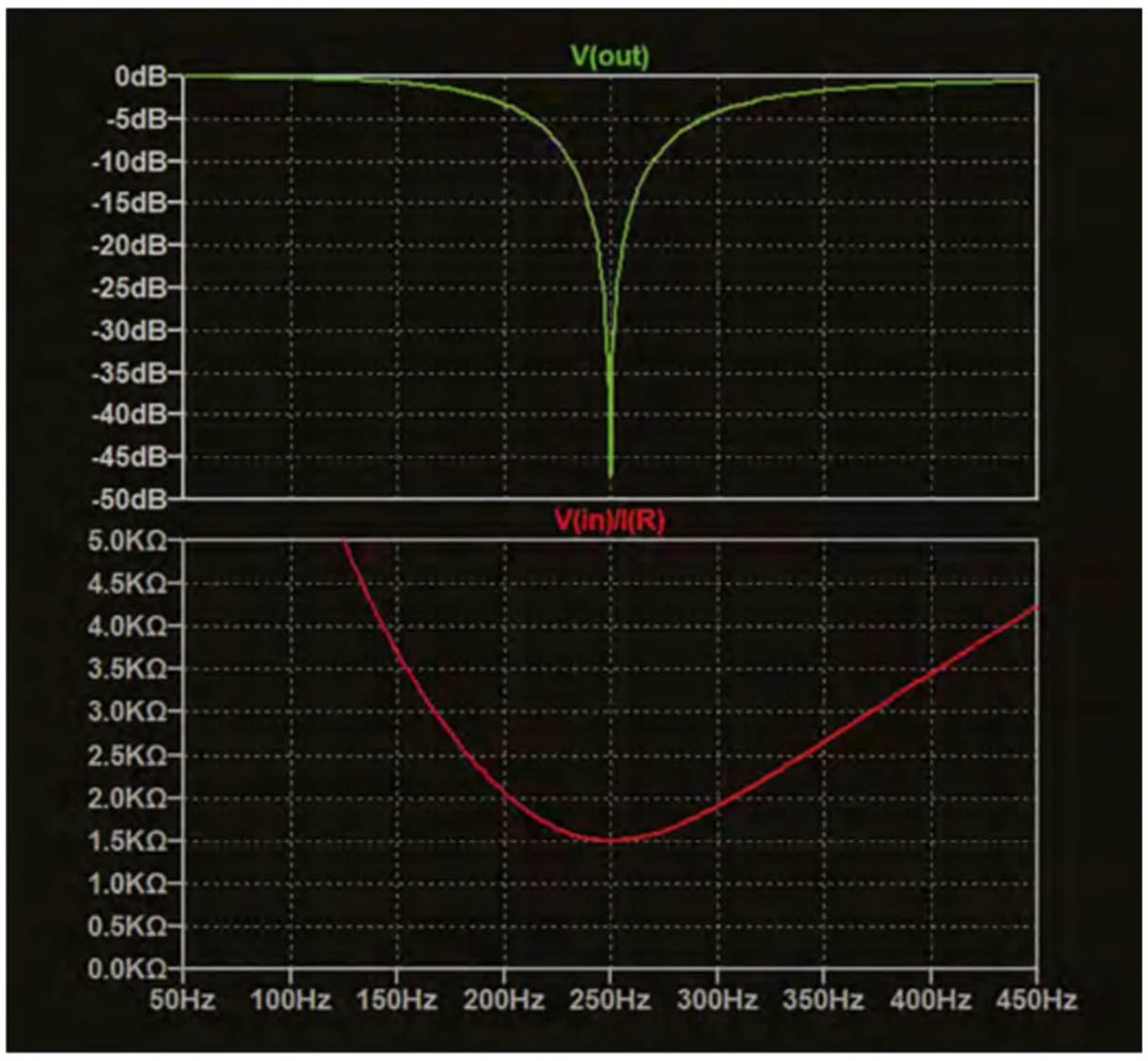


Fig.14. Simulation results from circuit in Fig.13. Upper trace is gain from input to output, lower trace is resistance of *RLC* series circuit.

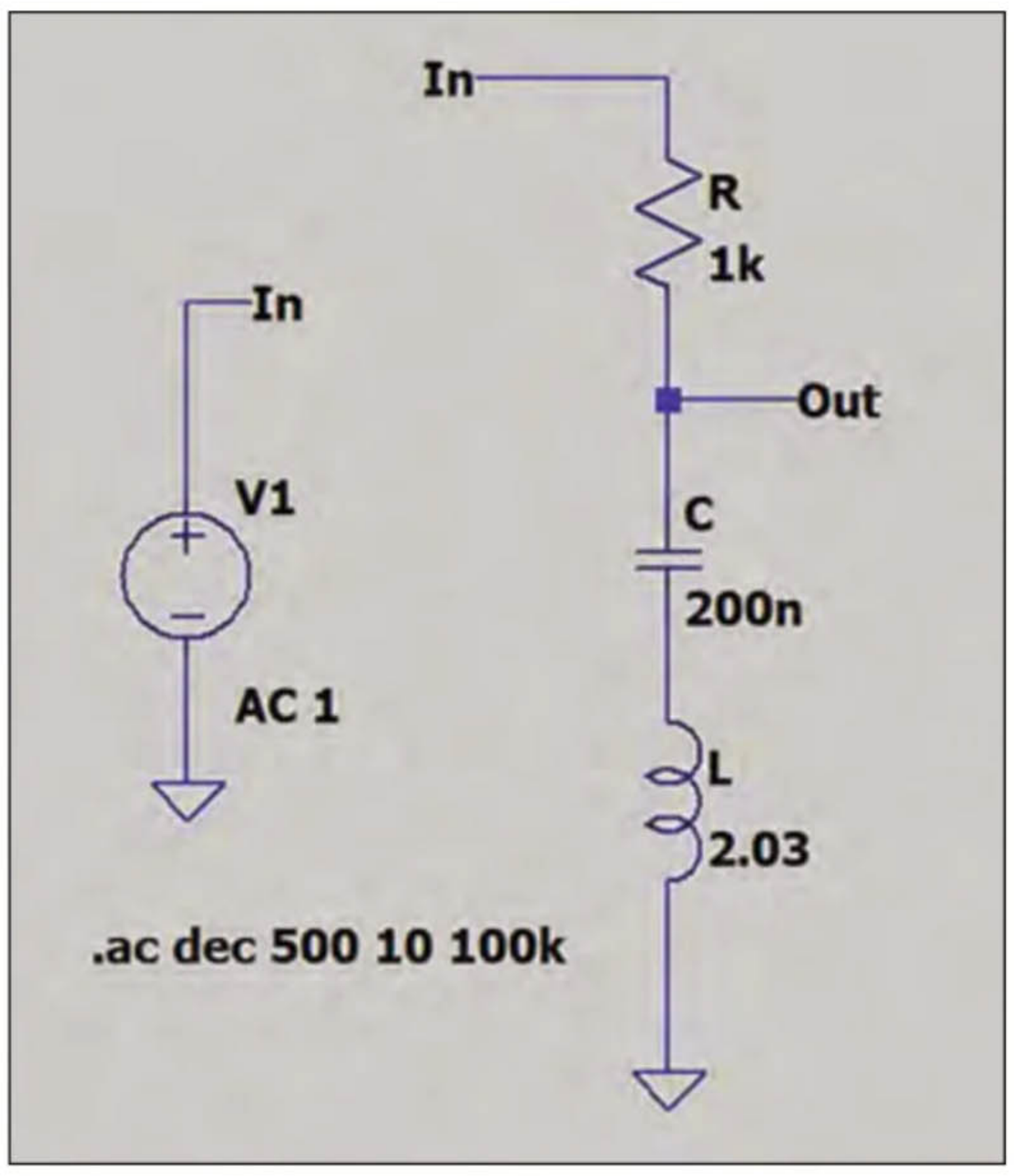


Fig.13. (left) Passive *RLC* notch (bandstop) filter.

value produces the same amount of cut or boost. For example, for R_G = 3kΩ (red traces) the gains are 3dB (boost) and –3dB (cut). The largest resistor value (1MΩ) provides close to unity gain (0dB).

RLC notch

For an equaliser circuit we need to be able to apply cut and boost in specific frequency bands with the same characteristics for cut and boost. If we replace R_G with a notch circuit – one that has very high impedance at all frequencies apart from a narrow range, where the impedance is low – then the cut/boost circuit will have unity gain at most frequencies (near infinite R_G). However, around the notch frequency the low value of the circuit impedance will result in either increased gain or increased attenuation, depending on the wiper position, in accordance with the discussion in the previous paragraphs. Of course, with the wiper at the centre of the potentiometer the gain will be unity – this will apply at all frequencies.

The required notch behaviour can be obtained using an *RLC* series circuit. This well-known circuit is show as an LTspice schematic in Fig.13, configured as a bandstop filter. The centre frequency (*LC* resonant frequency) is given by:

$$f_0 = \frac{1}{2\pi\sqrt{LC}}$$

If we want f_0 = 250Hz and we choose C = 200nF then L is given by $1/(2\pi f_0)^2C$ = 2.03H. We set R = 1kΩ, somewhat arbitrarily. The simulation plots in Fig.14 show the gain and the resistance of the series combination of the resistor, capacitor and inductor close to f_0. We see the sharp notch bandstop gain response, and the fact that the series resistance is minimum at f_0 and is equal to R. Since we are using an ideal inductor and capacitor, their combined impedance is zero at f_0 in this circuit. The maximum attenuation (notch depth) shown in this simulation depends on the number of data points – the more datapoints there are the closer they are likely to be to the exact value of f_0 (ideal infinite attenuation).

Cut/boost with RLC

When the *RLC* series circuit is used in place of R_G in the cut/boost circuit, as shown in Fig.15, we are using the impedance variation of the whole circuit to control the gain – an output is not taken from the potential divider formed by R and *LC* as it is in the circuit Fig.13. At resonance (f_0) the *RLC* series circuit has its minimum impedance (equal to R), which will result in the maximum cut or boost for the circuit in Fig.15. Thus, the maximum cut/boost of the circuit in Fig.15 is set using R_G in exactly the way as for the circuit in Fig.4 and Fig.8. Therefore, if we use the same values for the resistors as in Fig.8 (as described above) we will obtain a cut/boost filter with a maximum gain or attenuation of ±12dB.

The centre frequency for cut/boost for the circuit in Fig.15 is found using the *LC* resonance frequency equation given above. If we use the same values as for the circuit in Fig.13 we will obtain a cut/boost filter with a centre frequency of 250Hz. These values are used in the LTspice circuit in Fig.16. This is configured to step through a set of potentiometer wiper positions in the same way as for the circuit in Fig.8. The results in Fig.17 shows the frequency response at the various potentiometer settings. We see that the response can be adjusted from bandstop, through flat unity gain to bandpass. The maximum gain and attenuation is ±12dB, as designed. The circuit has unity gain at frequencies well away from the centre frequency, irrespective of the potentiometer position.

For a graphic equaliser we need to be able to control multiple frequency bands. Fortunately, this is easy to do with the circuit in Fig.12 – we just add more potentiometers and *RLC* circuits in parallel, as shown in Fig.18. The fact that there is zero volts across the potentiometers minimises their interaction, so that each potentiometer and its associated *RLC* circuit can

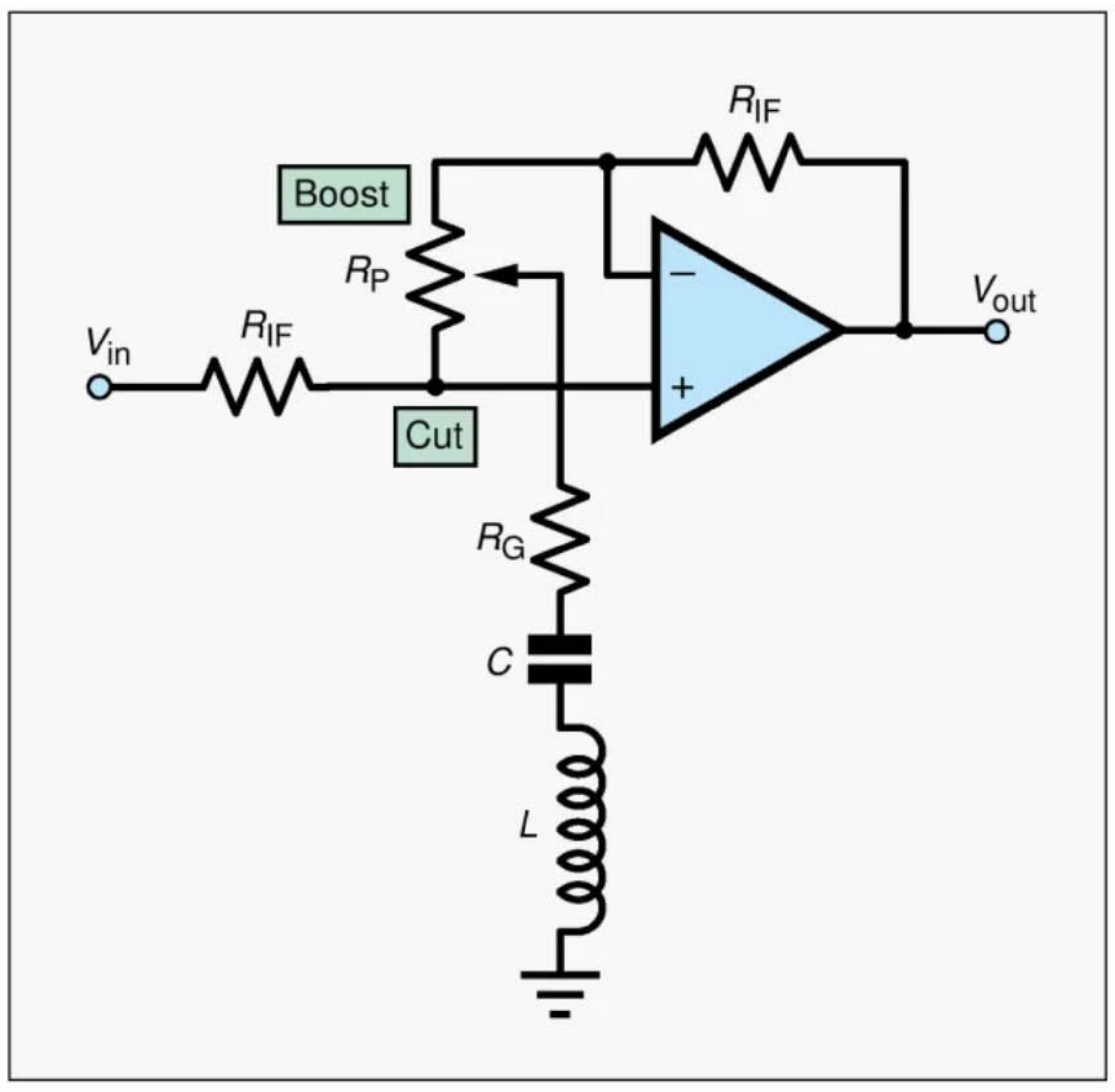


Fig.15. Cut/boost bandstop/bandpass filter.

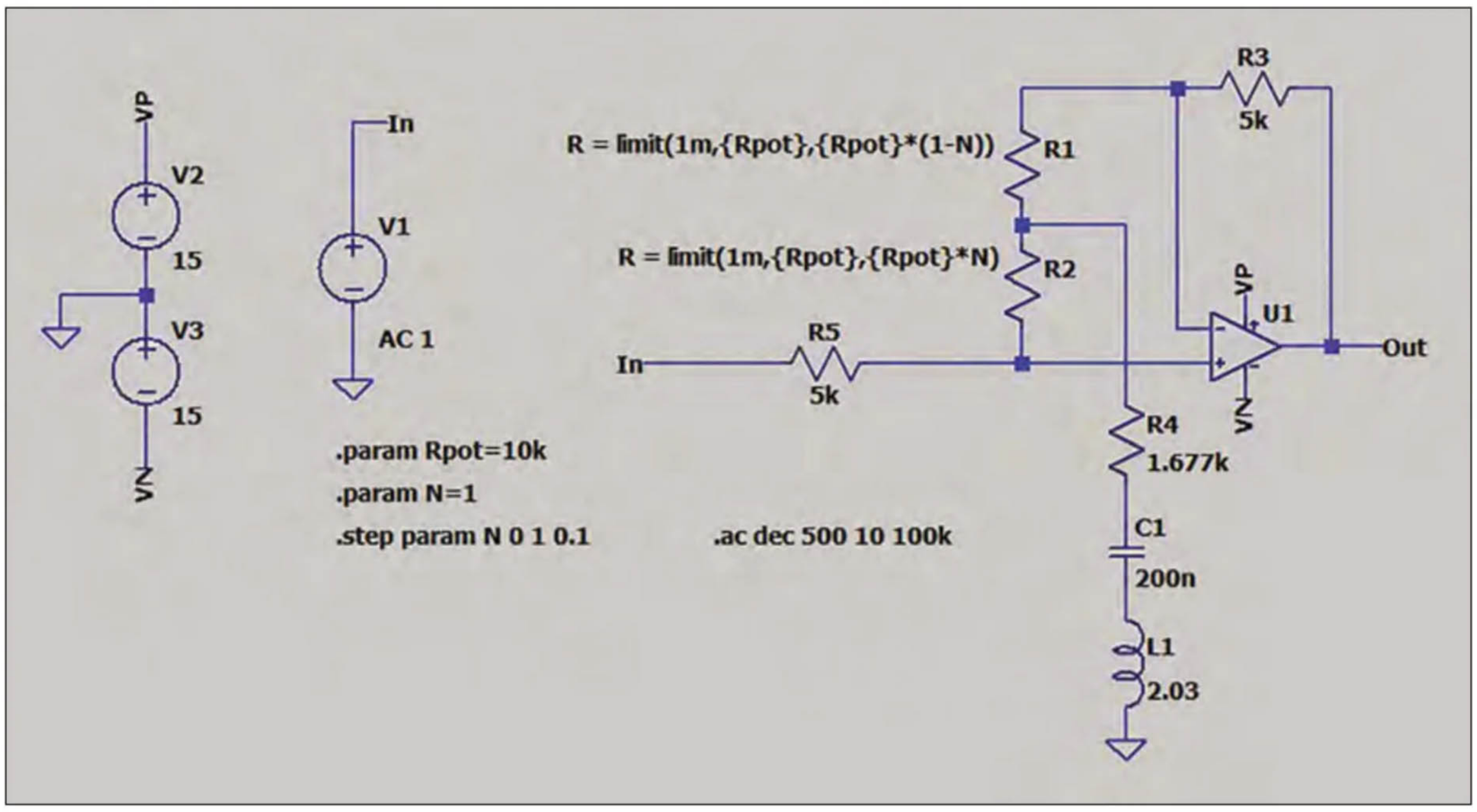


Fig.16. LTspice schematic for simulating the cut/boost filter in Fig.15.

provide reasonably independent control over a different frequency band. The interaction between the circuits for bands is not zero; one effect is to reduce the maximum gain/attenuation from the value applicable for a single band filter with the same R_{IF} and R_G. This can be accounted for by designing for a slightly higher gain.

The responses of adjacent bands need to overlap sufficiently so that if their gains are set the same the response is close to flat across those bands. If the filters for each band have too sharp a peak there will be gaps between them where the gain cannot be controlled. If the responses are too flat there will be too much interaction between controls for adjacent bands and it will be difficult to independently adjust adjacent bands. In practice, even with suitable filters, the response will not be perfectly flat with all the gains set equally – there will be some ripple in the gain. Although the ideal case is no ripple it is not as important as it might seem because the point of graphic equalisers is to adjust different bands differently, so a flat response is not the typical set up.

The sharpness of a frequency response peak is measured by the Q (quality) factor which is defined as f_0/BW, where f_0 is the centre frequency and BW is the bandwidth, defined as the frequency range between the points where the gain falls to 3dB below the peak on both sides. The larger the Q the sharper the peak. The appropriate Q value for the filters in a graphic equaliser depends on the closeness of the bands (octave, half octave…). For octave bands, values of Q around 1.5 to 2 are probably suitable (different sources vary on the values to use). The Q for an RLC filter is given by:

$$Q = \frac{2\pi f_0 L}{R}$$

This implies, for the circuit in Fig.16 and Fig.18 that resistor R_G controls both the Q and the full cut/boost gain. An equaliser circuit can be designed by finding R_G as above, then using the required Q and f_0 to find L for each band, and then the LC circuit f_0 (resonance) equation to find C in each case.

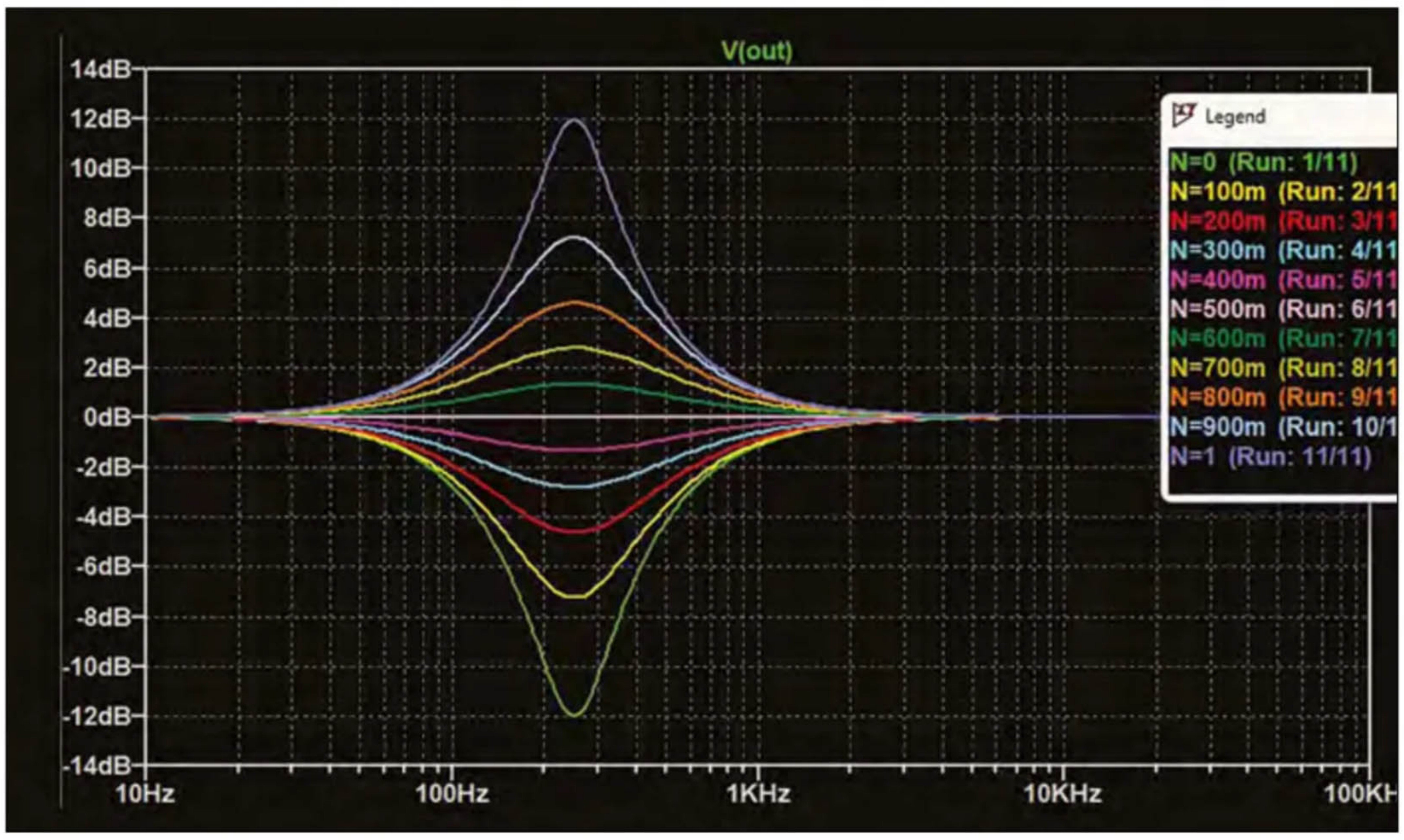


Fig.17. Simulation results for the circuit in Fig.16.

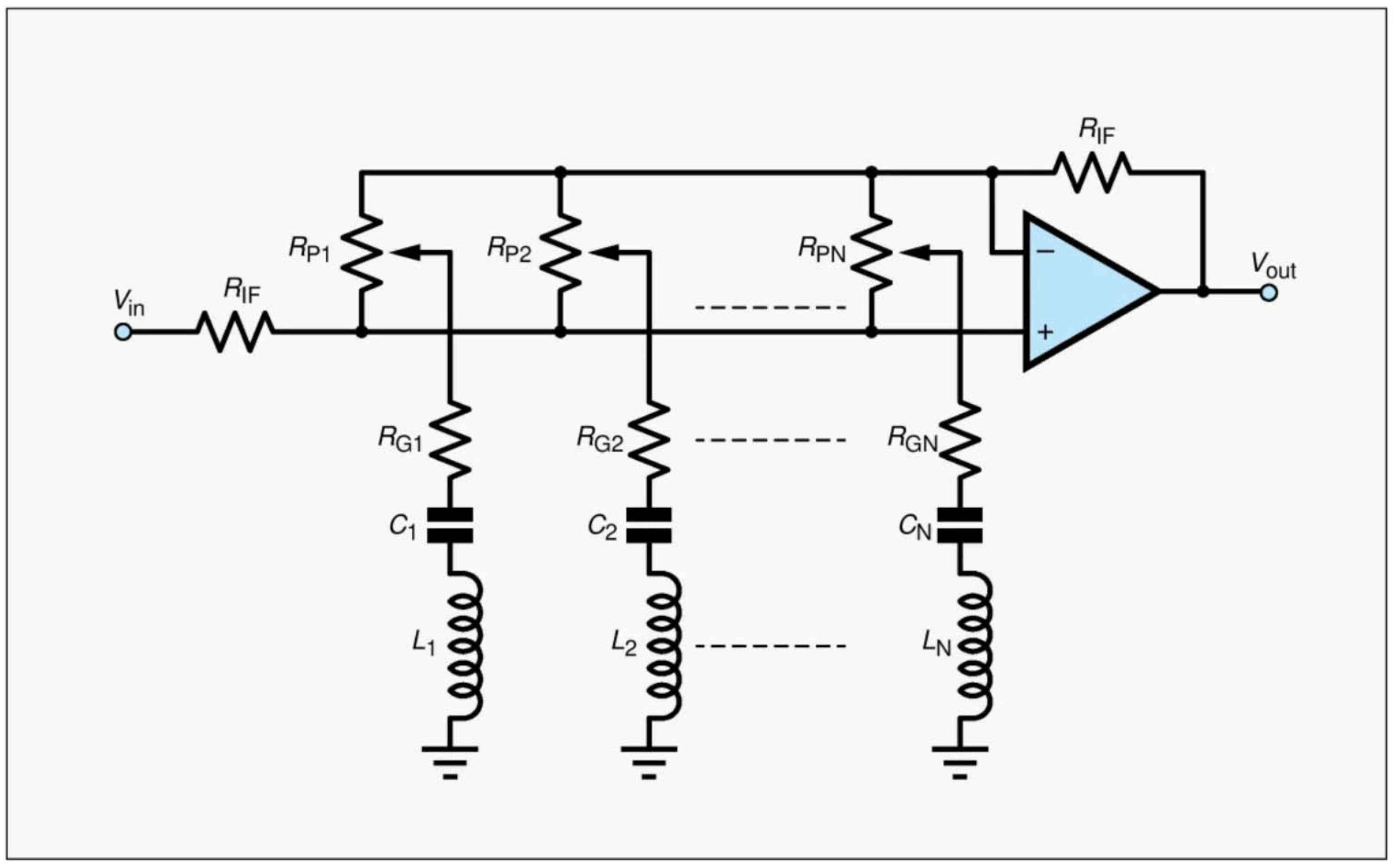


Fig.18. Graphic equaliser using cut/boost circuit with multiple gain-control filters.

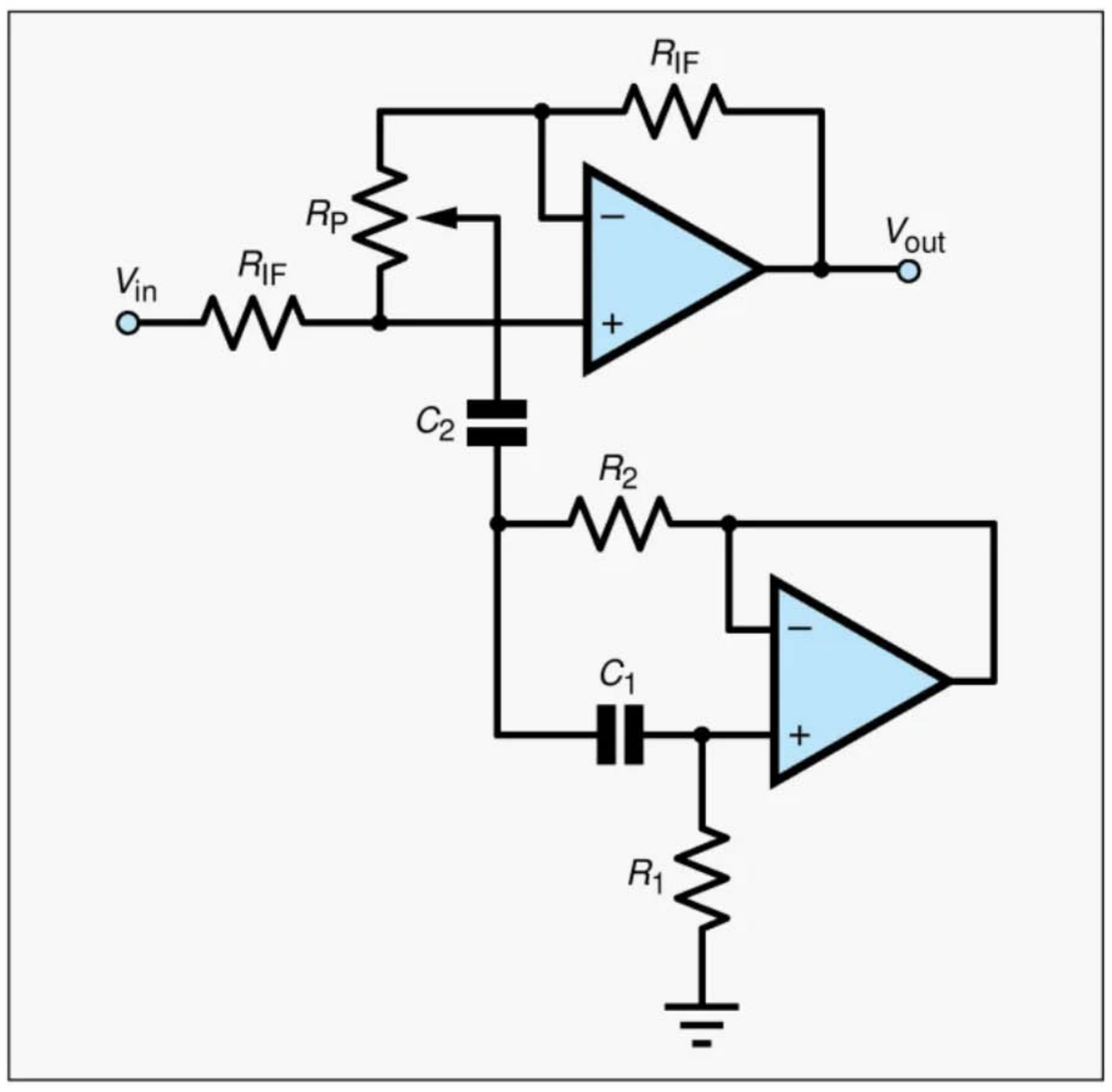


Fig.19. Cut/boost filter using a gyrator instead of an inductor.

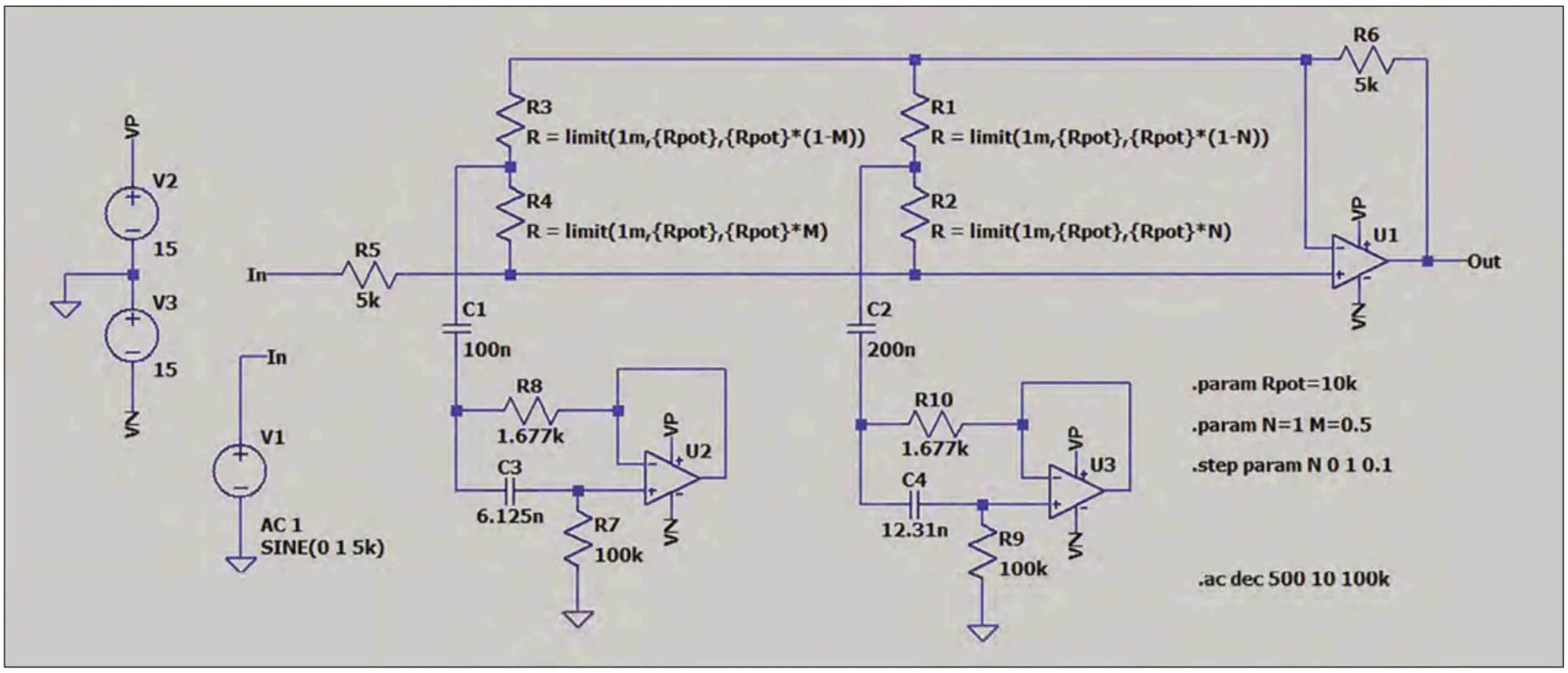

R6
5k
R3
R = limit(1m,{Rpot},{Rpot}*(1-M))
R1
R = limit(1m,{Rpot},{Rpot}*(1-N))
R4
R = limit(1m,{Rpot},{Rpot}*M)
R2
R = limit(1m,{Rpot},{Rpot}*N)
VP
V2
15
V3
15
VN
In
R5
5k
C1
100n
C2
200n
U1
Out
In
V1
AC 1
SINE(0 1 5k)
R8
1.677k
C3
6.125n
R7
100k
U2
R10
1.677k
C4
12.31n
R9
100k
U3
.param Rpot=10k
.param N=1 M=0.5
.step param N 0 1 0.1
.ac dec 500 10 100k

Fig.20. LTspice circuit for simulating a two-band equaliser circuit.

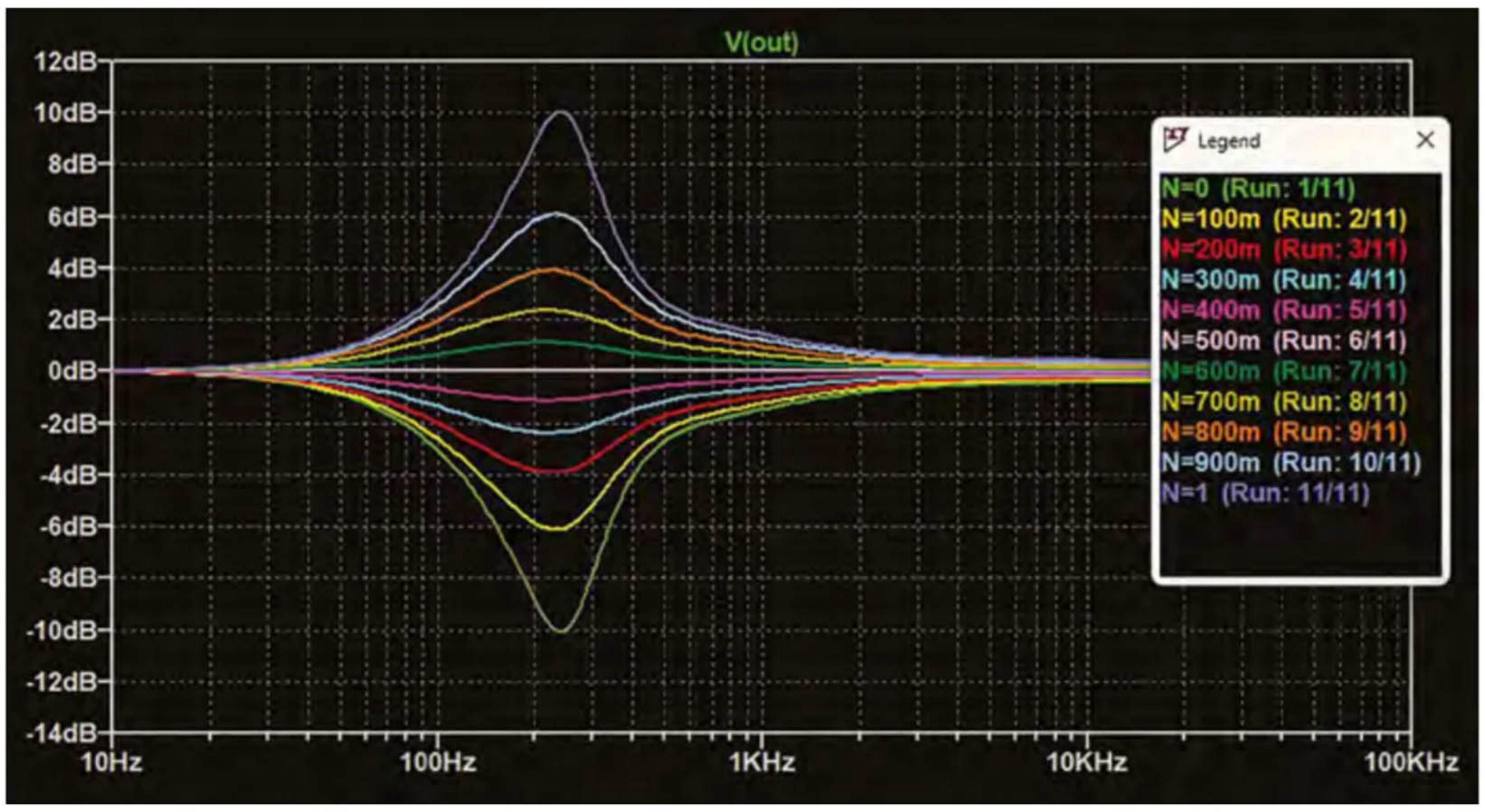


Fig.21. Simulation results from the circuit in Fig.19 with *M* = 0 (unity gain in 500Hz band).

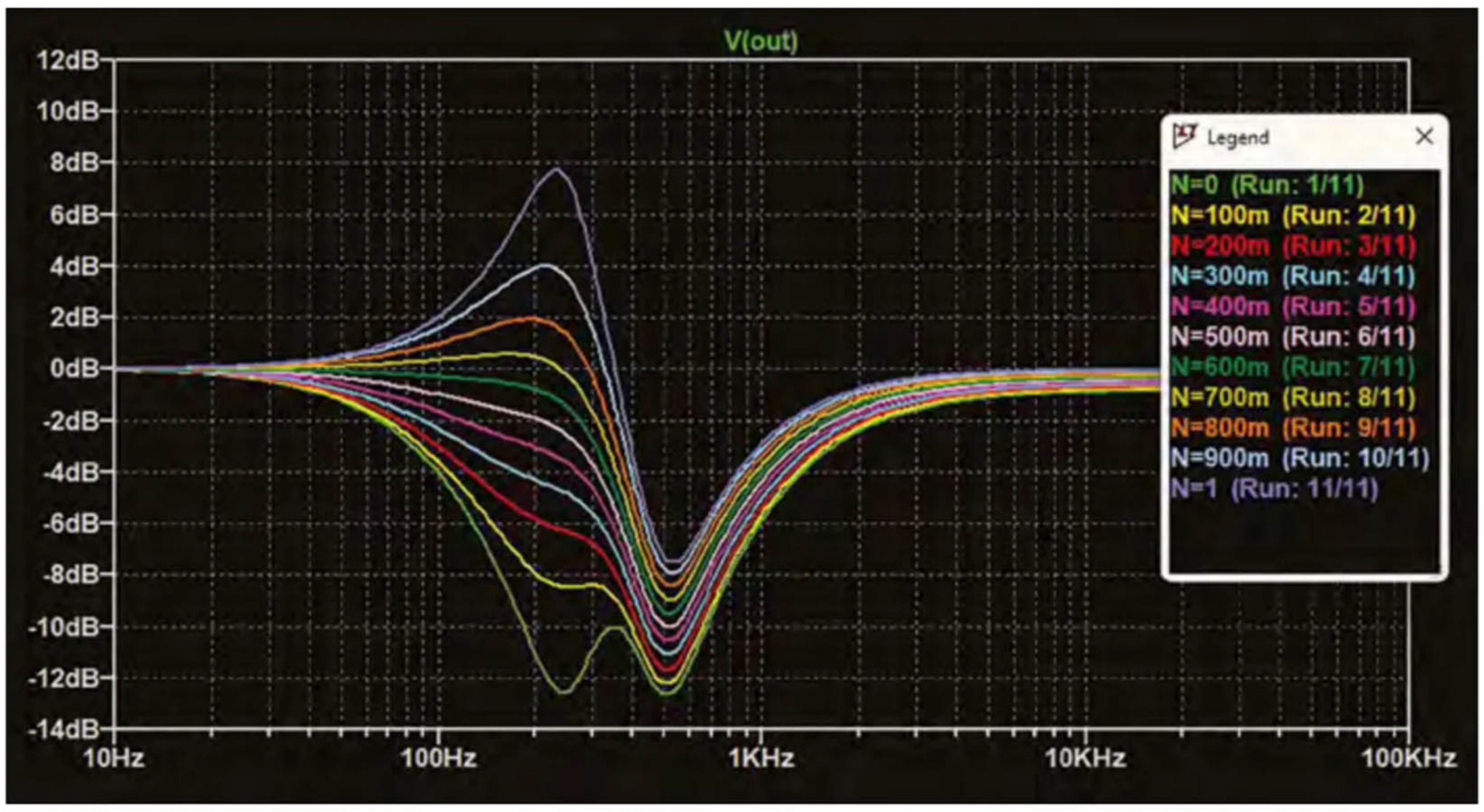


Fig.22. Simulation results from the circuit in Fig.19 with *M* = 0 (maximum cut in 500Hz band).

Using gyrators

Finally, we get back to the gyrator. An advantage of the circuits in Fig.16 and Fig.18 is that they have grounded inductors, which means that we can replace the inductors with gyrators, as shown in Fig.19. We do not need a separate R_G resistor because the series resistor in the gyrator (R_2 in Fig.2 and Fig.19) takes on this role. The circuit design follows the procedure just described (with R_G replaced with R_2). R_1 is typically a relatively large value, for example 100kΩ, as used last month. When the inductor value is found this is used to set C_1 in the gyrator, using the required L plus R_1 and R_2 in the inductor equivalence formula. C_2 in Fig.19 is found in the same way as C for the *RLC* version.

Fig.20 shows an LTspice circuit for a cut/boost 'equaliser' with just two octave bands centred on 250Hz and 500Hz, both with a nominal maximum cut/boost of ±12dB (same values as in Fig.16). The 250Hz band has the same *RLC* capacitor as in Fig.16 (200nF) and the gyrator capacitor is based on the 2.03H inductor value from that circuit using: $C_1 = L/(R_1 - R_2)R_2 = 2.03/((100\text{k} - 1.677\text{k}) \times 1.677\text{k}) = 12.31\text{nF}$ in the gyrator. The 500Hz stage was designed in the same way.

The simulation uses parameters for wiper positions for both bands, but currently the 250Hz band is stepped and the 500Hz band is fixed. The specific values in Fig.20 results in unity gain in the 500Hz band ($M = 0.5$). Fig.21 shows the results, which ideally would be the same as those in Fig.18. There are some differences – in particular the peak gain is lower due to the presence of the other potentiometer and gyrator. Fig.22 shows what happens with $M = 0$ (full cut fixed on the 500Hz band). Note the ripple in the full-cut-in-both-bands case (green trace at the bottom of Fig.22) – ideally this would be flat from 250 to 500Hz as discussed above. Fig.22 illustrates the wide range of response shapes which can be obtained using multiple cut/boost filter bands. Most real equalisers would have more bands.

Simulation files

Most, but not every month, LTSpice is used to support descriptions and analysis in *Circuit Surgery*.
The examples and files are available for download from the *PE* website.

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Full-wave 10A Universal Motor Speed Controller	10102181	£12.90
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Next Month – in the November issue

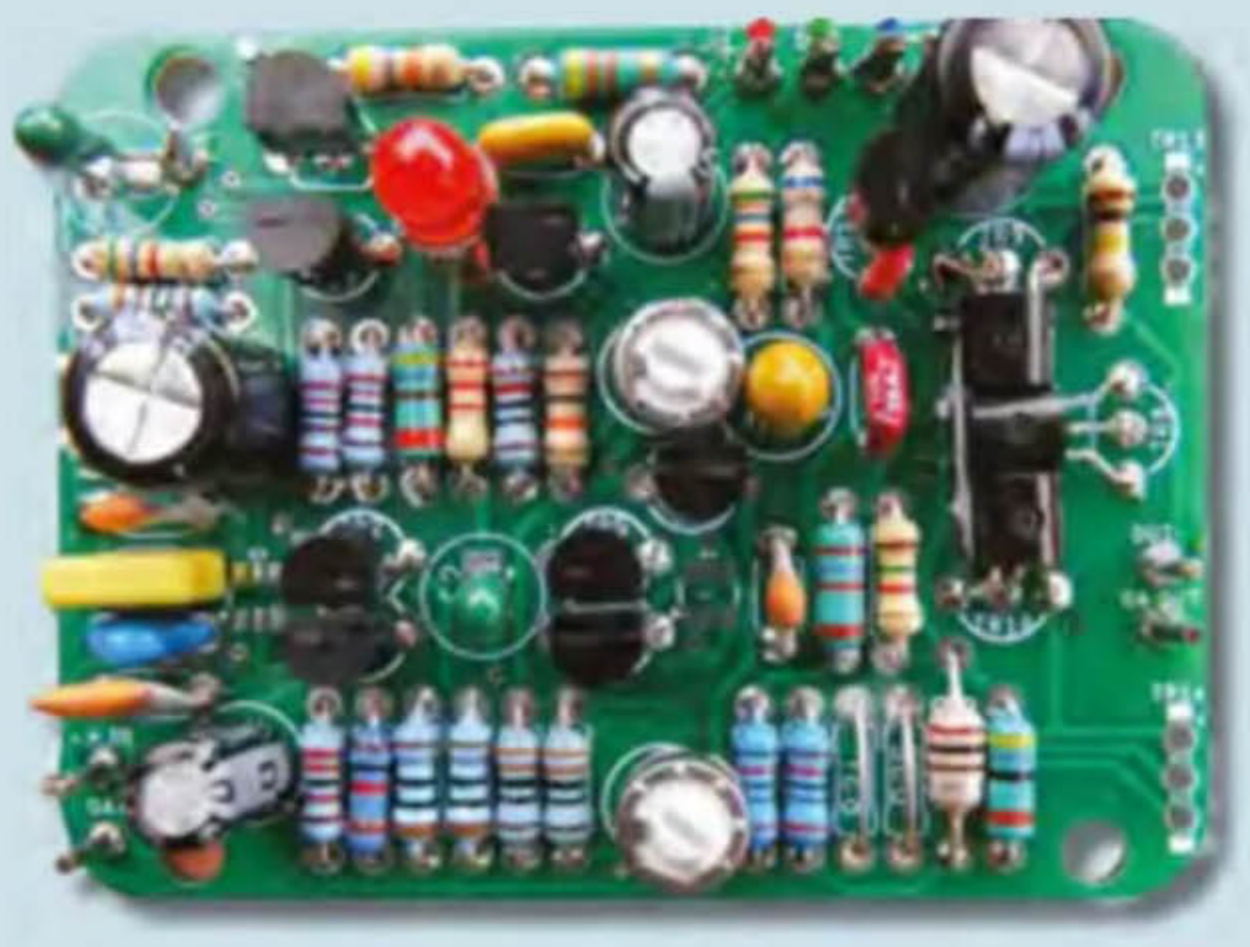
LC METER MK3
CAP
CAL / START
C
L
OPTION 1
NORMAL
OPTION 2
ON

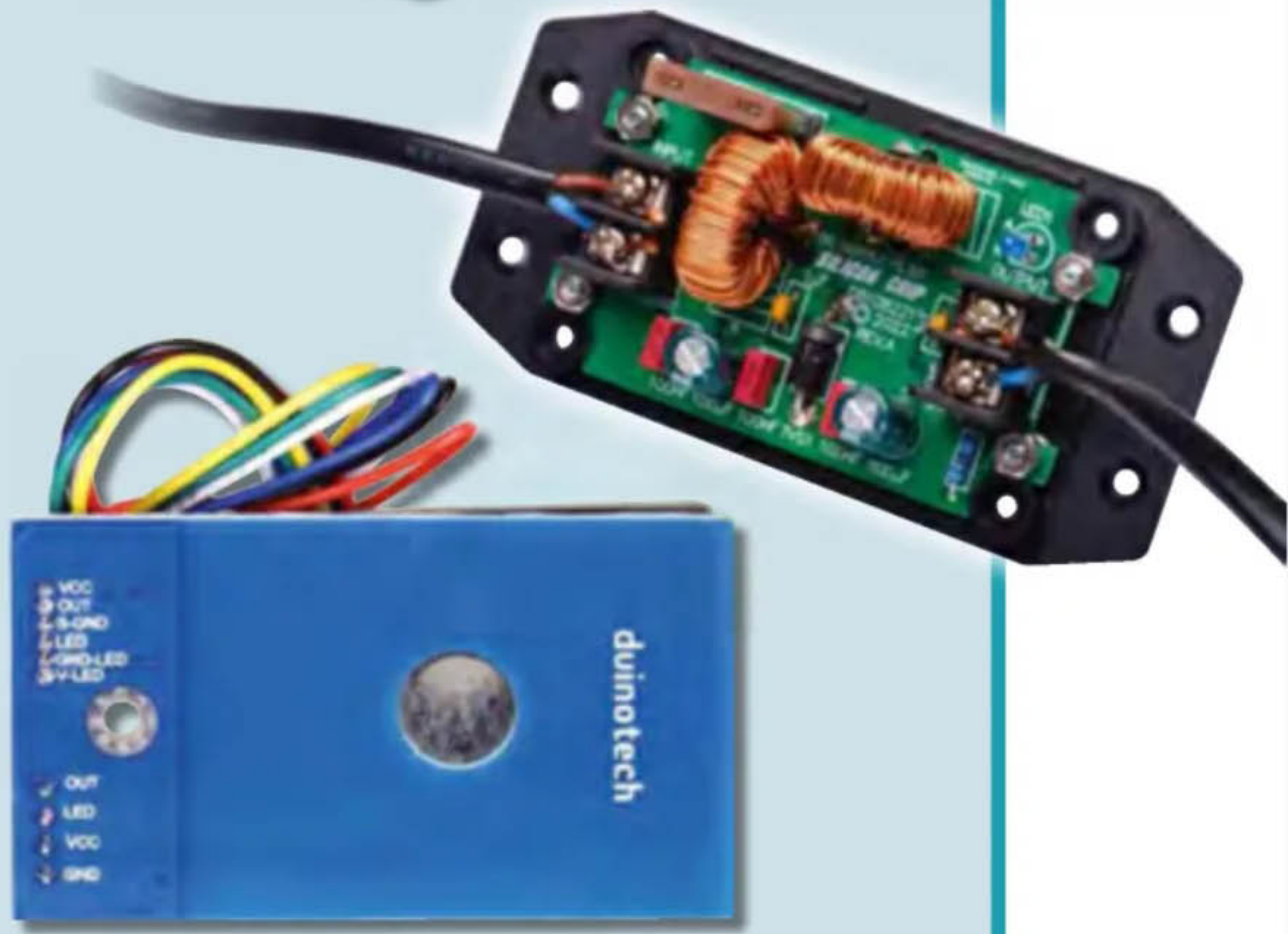
LC Meter Mk3

This new LC (inductance/capacitance) Meter is a modernised version of a very old design - the Tektronix T130 from the 1950s. It can measure a wide range of capacitances and inductances, from less than 1pF to more than 1.2nF, and from less than 100nH to more than 2.5mH. It displays the results on an OLED screen.

DC Supply Filter for vehicles

Many devices will run off 12V DC, so it's pretty tempting just to plug them into a vehicle supply (via a cigarette lighter socket or similar), and away you go. But you're likely to run into two significant problems with that: supply noise messing with the device's performance and voltage spikes possibly frying it. This Filter solves both those problems.





PM (particulate matter) 'Dust' Sensors

In this last article on low-cost air quality sensors, we look more closely at particulate matter (PM) sensors, also called 'dust' or 'smoke' sensors.

Discrete audio op amp – Part 3

Next month, we conclude Jake Rothman's innovative discrete op amp project with assembly, testing and extended power options.

PLUS!

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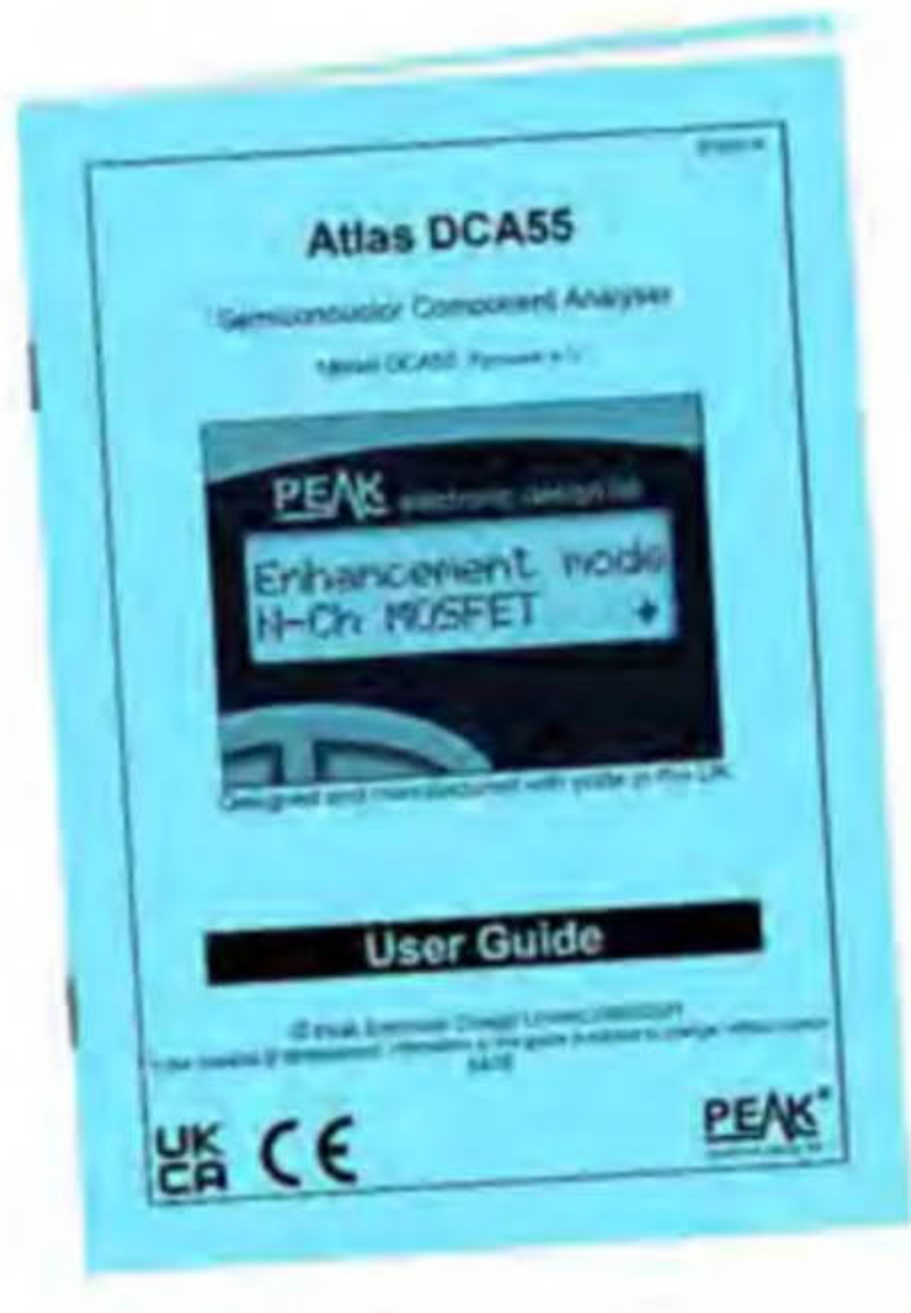
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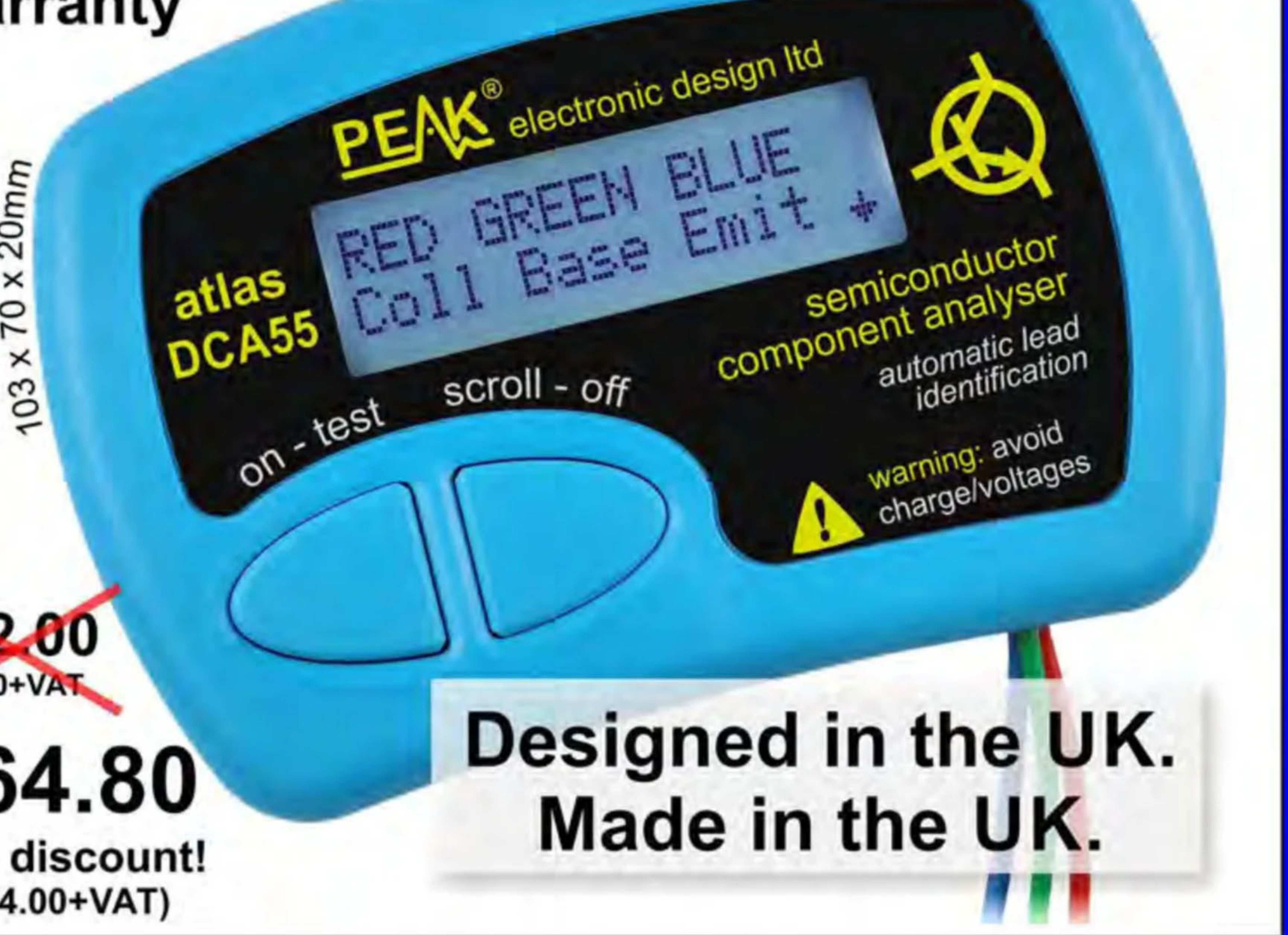

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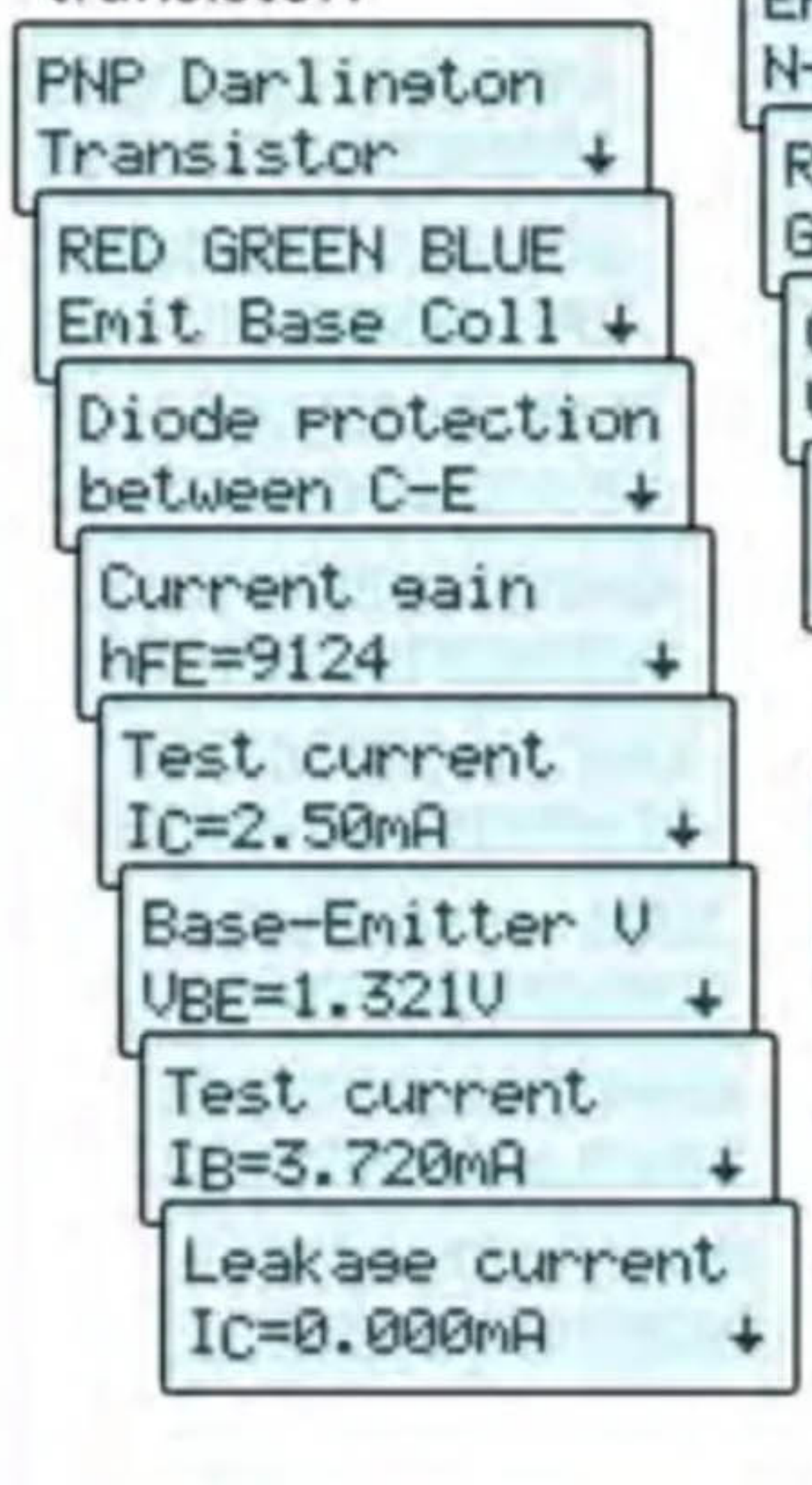
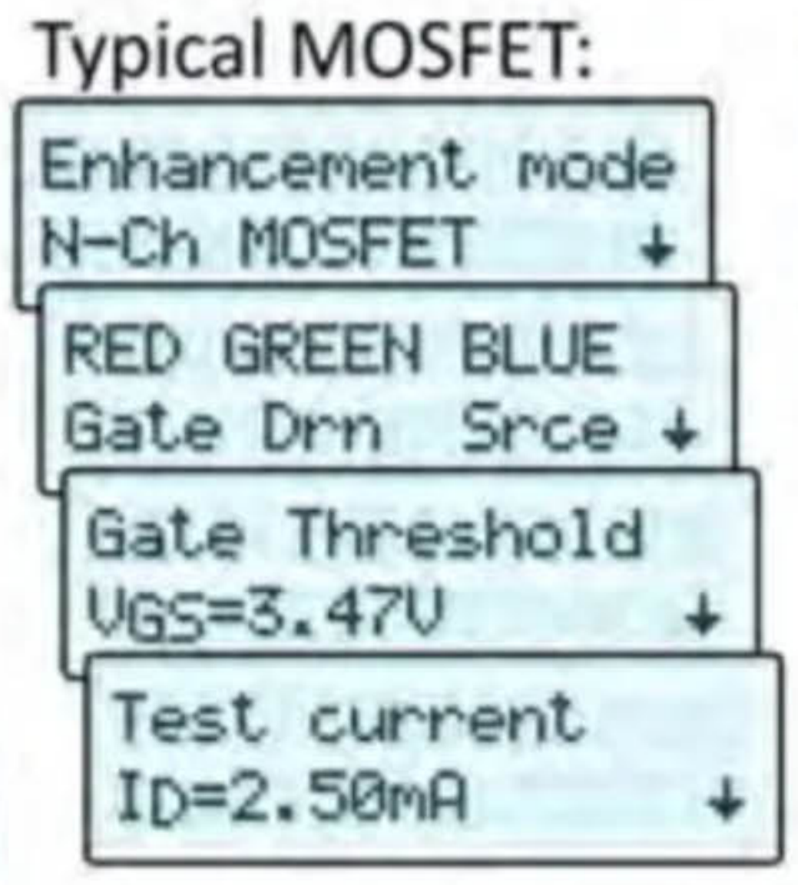


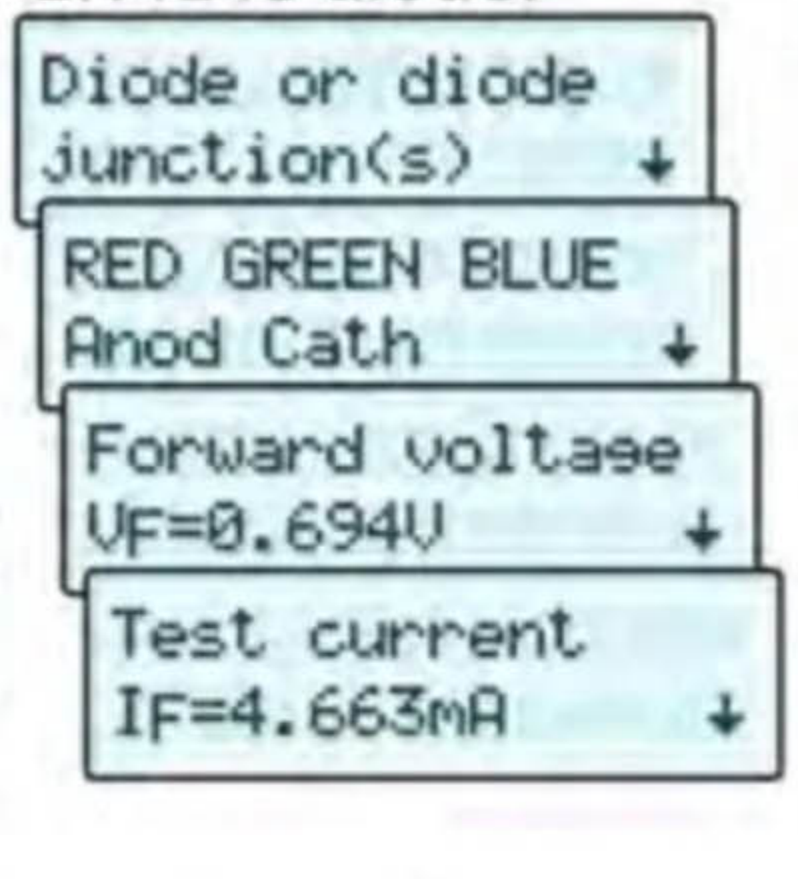
```
PNP Darlington
Transistor      ↓
RED GREEN BLUE
Emit Base Coll  ↓
Diode protection
between C-E     ↓
Current gain
hFE=9124        ↓
Test current
IC=2.50mA       ↓
Base-Emitter V
VBE=1.321V      ↓
Test current
IB=3.720mA      ↓
Leakage current
IC=0.000mA      ↓
```

Typical MOSFET:



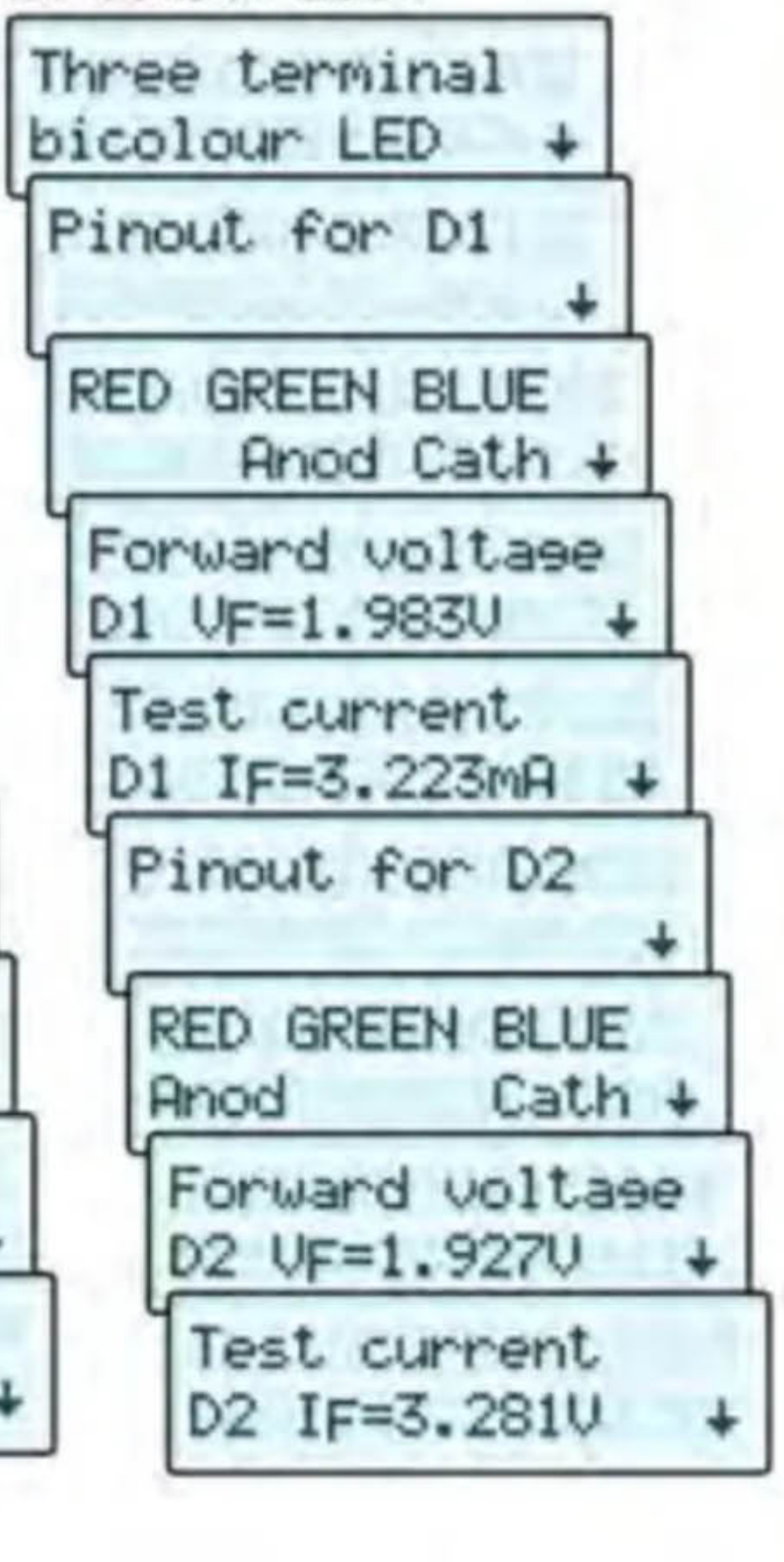
```
Enhancement mode
N-Ch MOSFET     ↓
RED GREEN BLUE
Gate Drn  Srce  ↓
Gate Threshold
VGS=3.47V       ↓
Test current
ID=2.50mA       ↓
```

1N4148 diode:



```
Diode or diode
junction(s)     ↓
RED GREEN BLUE
Anod Cath       ↓
Forward voltage
VF=0.694V       ↓
Test current
IF=4.663mA      ↓
```

Bi-colour LED:



```
Three terminal
bicolour LED    ↓
Pinout for D1
                ↓
RED GREEN BLUE
     Anod Cath  ↓
Forward voltage
D1 VF=1.983V    ↓
Test current
D1 IF=3.223mA   ↓
Pinout for D2
                ↓
RED GREEN BLUE
Anod      Cath  ↓
Forward voltage
D2 VF=1.927V    ↓
Test current
D2 IF=3.281V    ↓
```

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